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A Qualitative Approach for Investigating Thermal Discomfort in the Outdoor Environment of a World Heritage Site: A Case Study of Hampi, India

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Abstract

The outdoor thermal environment affects visitors' thermal comfort and overall experience. This study investigates the application of photographic analysis as a qualitative tool for evaluating thermal discomfort in outdoor environments at a World Heritage Site. Thermal discomfort is a key concern in public settings as global temperatures continue to rise. At the same time, traditional approaches rely on microclimate measurements and user feedback. However, this study takes a more subjective, visual approach to capturing and interpreting how visitors experience thermal comfort or discomfort in large-scale archaeological sites. This research uses photographic data to identify and analyze the primary visual signs of thermal discomfort. Results reveal that visitors in the heritage site experience strong heat stress during the winter season. Despite the study area experiencing strong heat stress and visitors feeling hot and warm, the majority of the visitors are satisfied with the thermal conditions of the heritage site. Photographic analysis reports that the most common signs of thermal discomfort are mostly related to intense solar radiation and the absence of shade. The research findings can be used to develop strategies for reducing thermal discomfort while maintaining the cultural and historical integrity of heritage places. The research underscores the importance of visual data in comprehending the interplay between thermal comfort, environmental design, and visitor experiences in culturally significant sites.

Keywords: thermal discomfort; photographic analysis; qualitative research; World Heritage Site

Introduction

Climate change, caused by global warming, has a wide range of consequences on human life. As temperatures rise, stresses from heat and heat-related mortality increase (Kleerekoper et al., 2012). In the years ahead, designers and planners will face the difficulty of creating the conditions required for outdoor thermal comfort, or "that state of mind which expresses satisfaction with the thermal environment" (ISO, 2005). Earlier studies focused on the physiological aspects of thermal comfort, while recent ones have highlighted psychological factors (Hirashima et al., 2016). Qualitative and quantitative studies are essential for gaining a deeper understanding of people's subjective experiences. Numerous studies on outdoor heat perception have integrated these approaches (Ali & Patnaik, 2018; Banerjee et al., 2022;

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Kumar & Sharma, 2021; Manavvi & Rajasekar, 2020). Studies on microclimate and outdoor thermal comfort have primarily focused on environments such as residential neighborhoods (Colter et al., 2019; Singh et al., 2024; Zhang & Liu, 2021), parks and open spaces (Ali & Patnaik, 2018; Aram et al., 2020; Johansson et al., 2018; Niu et al., 2022; Yuan et al., 2023), university campuses (Eslamirad et al., 2022; Ghaffarianhoseini et al., 2019; Jing et al., 2024; Othman et al., 2021), street canyons (Abdollahzadeh & Biloria, 2021; Deng & Wong, 2020; Miao et al., 2023; Mohite & Surawar, 2024), traditional vernacular settlements (Huang et al., 2018; Sözen & Koçlar Oral, 2019) and low income settlements (Banerjee et al., 2020, 2022). The existing literature reports numerous studies on thermal comfort in urban microclimates; however, limited studies have focused on enhancing tourist sites. According to Kumar and Sharma (2020), only 4% of studies have dealt with outdoor thermal comfort in tourist sites, based on research conducted between 2001 and 2019. Tourists are highly vulnerable to heat exposure, as heat-related health hazards are becoming increasingly complex and severe (Hondula et al., 2017). Thus, it becomes increasingly important to study its climatic characteristics and outdoor thermal comfort analysis. Considering thermal comfort analysis in tourist site planning and development can enhance the comfort condition and improve visitor experience (Nikolopoulou & Steemers, 2003). Outdoor thermal comfort studies on tourist sites mainly focused on beaches (Rutty & Scott, 2014, 2015; Zhang et al., 2023), parks (Wei et al., 2022), and heritage sites (Binarti et al., 2021; Fabbri et al., 2020; Manteghi et al., 2020; Manteghi & Mostofa, 2022; Nasrollahi et al., 2017). Furthermore, in countries like India, despite having a large number of heritage sites, there is a lack of adequate studies on outdoor thermal comfort in tourism settings. Most of the world heritage sites are large protected areas, and after the excavations, the areas appear like barren land. As many tourists visit these places and consider the projected rise in temperatures, improving Outdoor Thermal Comfort (OTC) is essential and worthy of investigation because tourists are exposed to the harsh climate year-round.

World Heritage Sites (WHS) are designated for cultural, historical, and architectural significance. These locations draw millions of visitors annually, who enjoy both the aesthetic appeal and the environmental conditions in these areas. Thermal discomfort caused by extreme temperatures or humidity is one of the most serious issues in outdoor environments, as it impacts visitor comfort, well-being, and overall satisfaction. However, measuring thermal discomfort in such scenarios is challenging, as it involves considering both environmental factors and individual sensations of discomfort (Fabbri et al., 2020). Thermal discomfort in outdoor environments refers to situations that make people feel uncomfortably hot or cold, generally caused by environmental elements such as air temperature, humidity, wind, and exposure to the sun. This phenomenon is significant at heritage sites, where preserving cultural and architectural integrity must be maintained with visitor comfort and health.

The International Council on Monuments and Sites (ICOMOS) recommends that tourism activities prioritize visitor comfort, safety, and well-being while preserving significant features and ecological characteristics (ICOMOS, 2002). However, the factors contributing to thermal discomfort in outdoor heritage sites include climate and weather conditions, a lack of green spaces, and limited design options. Heritage site planning and redevelopment often focus on historical and aesthetic value, while neglecting thermal comfort. Researchers used visual research techniques in various academic disciplines, including urban studies. Historically utilized in ethnography and architectural studies, photographic analysis has proven to be a valuable qualitative tool for documenting a site's physical and social elements (Pink, 2015). Based on the theory of semiotics, photographic analysis is employed to investigate the processes of visual interpretation of built and vegetated environments related to people's outdoor thermal adaptation. Semiotics is the study of signs. Anything that creates meaning or can represent something else is a sign. Photographs are the signs in this case (Shooshtarian, 2019). Based on this theory, Cortesão et al. (2020) evaluated the outdoor thermal environment using photographic comparison, where participants interpreted the photographs. According to the researcher, signs of thermal comfort or discomfort can be visible in photographs, such as vegetation, shading, and predominant colours. Results show that photographic comparison (visual appraisal) confirmed the conclusions from the verbal method (field survey) (Cortesão et al., 2020). However, this method may not apply to the respondents in the tourist group.

Existing literature suggests that heritage sites are subject to high heat stress, as indicated by microclimate analysis. Binarti et al. (2021) conducted a thermal comfort survey at the World Heritage Archaeological Park (Prambanan Temple) in a tropical climate. Their study reveals that the andesite stone structures in the heritage site contribute to an increase in air temperature due to the thermal properties of the stones. The radiative properties of the stones cause thermal discomfort, making the outdoor environment uncomfortable for visitors. Moreover, the limited shading and large open areas in archaeological sites exacerbate the high temperatures. Fabbri et al. (2020) evaluated the role of vegetation in archaeological regions and its impact on visitors' thermal comfort using Physiologically Equivalent Temperature (PET) and microclimate analysis. They studied different scenarios with ENVI-met software and concluded that although PET values were high, scenarios with more vegetation and green areas improved thermal comfort. They report that vegetation cools the environment due to shading and the process of evapotranspiration. Vegetation lowers the air temperature, making the outdoor environment more comfortable for visitors. Lam et al. (2018) reported that foreign visitors experienced different thermal sensations and preferences than local visitors during hot weather. They also noted that visitors perceived the thermal environment as hot, yet 36.8% of European visitors preferred no change in thermal conditions.

Additionally, the presence of cooling elements, like shaded areas or water features, can alter the perception of thermal conditions, even if the actual microclimate remains unchanged. Furthermore, Manteghi et al. (2020) reported that in the Malacca heritage site, PET values exceeded the comfort range (<30°C). Despite the high air temperature, relative humidity, and higher PET range indicating an uncomfortable thermal environment, about 76% of foreign visitors were satisfied with the thermal conditions. Several studies on heritage sites report that visitors are psychologically compatible with the conditions despite the high heat stress (Karimi & Mohammad, 2022; Nasrollahi et al., 2017). Hence, this research aims to validate the visitors' responses from the thermal perception survey by analyzing the thermal environment using photographic analysis.

From the existing literature, we identified a need to explore the OTC use of tourists in large-scale archaeological sites. Previous research in India has focused on urban streets, neighbourhoods, parks, and open spaces. However, current narratives lack the discussion of tourism sites or heritage sites. As heritage sites or archaeological sites reveal a distant microclimate and spatial pattern for the outdoor spaces, they require special attention during revitalization. Therefore, there is a need for a contextual approach, which is lacking in heritage sites, particularly in India. The key signs of thermal comfort and discomfort can help designers and planners visualize the existing site conditions more effectively. We report that no comprehensive framework exists to explore the existing OTC conditions of tourists in heritage sites in India. Therefore, this study aims to explore the OTC use of tourists in heritage sites in India (Bsh Koppen) through photographic analysis, microclimate measurement, and a questionnaire survey.

Furthermore, we investigate the match between the respondents' behaviour and their thermal comfort votes through semiotic logic. It is a first-of-its-kind study that uses photographic analysis to assess outdoor thermal comfort conditions. We examine how photographic analysis validates qualitative outdoor thermal perception surveys by interpreting visual data.

Data and Methods

The present study utilized photographic data to analyze outdoor thermal comfort in a tourist destination. A pilot test was conducted on sunny days in multiple locations to evaluate the thermal conditions within a large-scale archaeological setting. The investigation aimed to identify thermal comfort issues in a large-scale archaeological site and further intends to yield more information on the spatial and behavioural patterns of the visitors.

Study Area

The Group of Monuments in Hampi (15°20′N and 76°28′E) is one of the UNESCO World Heritage Sites in India, with a tourist footfall of 9.9 lakh (990,000) domestic and 21,900 foreign tourists, according to the India Tourism Data Compendium 2024. Hampi is a small village with temples and ruins of the Vijayanagara kingdom, situated on the banks of the Tungabhadra river and bounded by hills on three sides. Hampi has two centres: the sacred center and the royal center. The sacred centre is situated along the river and consists of numerous temples, while the royal center is mainly the urban core of the Vijayanagara rulers. The site exhibits a semi-arid climate (Koppen Bsh). Hampi has an annual mean air temperature (T_a) of 32°C. Summers are very hot and dry, with an average temperature (T_a) of 37°C and an average relative humidity (RH) of 35-40%. During the summers, the T_a often exceeds 40°C. This higher T_a causes thermal discomfort during summer. Thus, tourist visitation declines during the summer season from March to May. Winters are generally the peak season when T_a ranges from 15 to 30°C. Tourist visitation increases from October to February. Tourists typically explore this World Heritage Site from 10:00 AM to 4:00 PM. Thus, we consider this heritage site a case study due to its large-scale archaeological setting, comprising more than 1600 monuments, and its significant tourist footfall, situated in an extreme climate to ensure year-round tourist footfall and enhance the tourist experience.

An outdoor thermal comfort survey was conducted at four key locations within a large-scale archaeological site in Hampi, India. We selected four famous locations for our research, namely Hampi Bazaar Street (study area A), Vittala Bazaar Street (study area B), the Royal Centre (study area C), and Kampa Bhupa's Path (study area D) (Figure 1). We conducted the study during the high tourism season in November to analyze a large number of visitors. Photographs were collected during the same time. Figure 2 shows the study framework. Table 1 tabulates the detailed description of the survey locations. We chose these four study areas to capture the spatial, behavioural and microclimatic differences due to variations in vegetation cover, exposure to climatic variables, availability of shade, and the morphology of the ruins. The Archaeological Survey of India (ASI) maintains these chosen heritage sites.

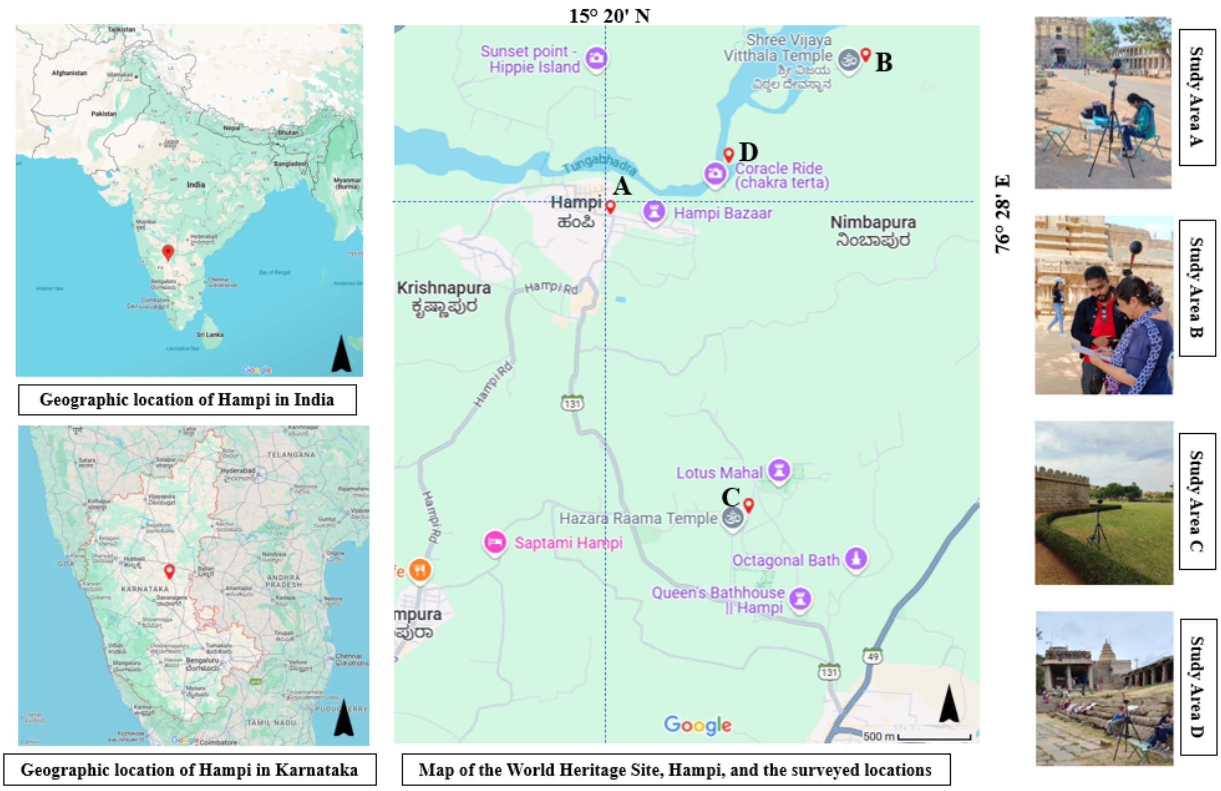

Figure 1. Location of Hampi in Karnataka, India and Survey locations
Study area A – D (Study area A - Hampi Bazaar Street (Partially shaded pathway), Study area B - Vittala Bazaar Street (Unshaded pathway), Study Area - C Royal Centre (Picturesque approach), Study Area D - Kampa Bhupa's path (Riverfront))

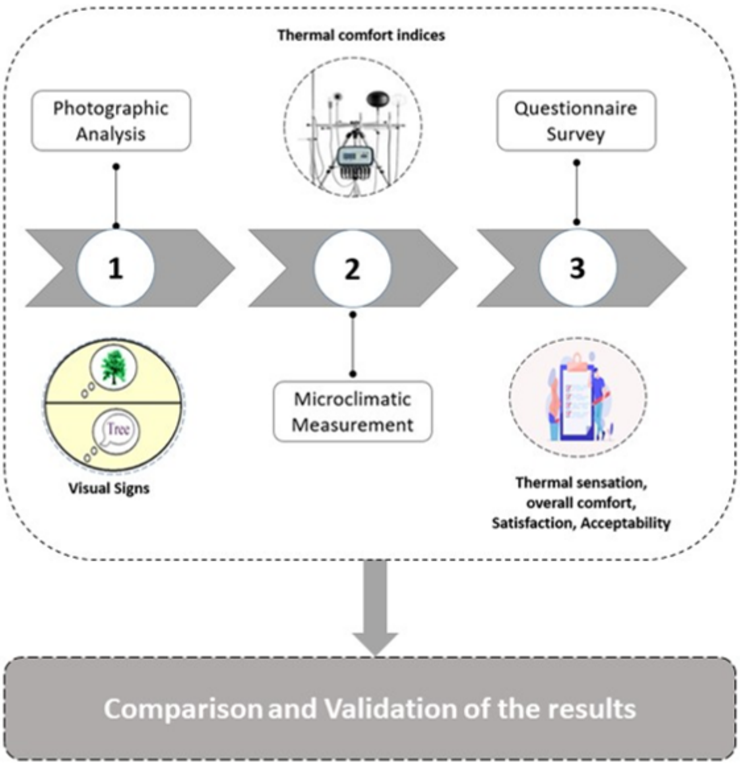

Figure 2. The study framework

Source: Authors

Table 1. Description of the study areas

Study area	Pavement	Vegetation	Distance from waterbody	Influencing factor
Study area A- (Hampi Bazaar Street)	Hard paved (Concrete)	Little vegetation along the walkway	100m	Partially exposed to all climatic variables
Study area B- (Vittala Bazaar Street)	Soft paved (Dry Sandy Soil)	Very nominal vegetation	200m	Fully exposed to all climatic variables
Study area C- (Royal Centre)	Soft paved (Grass & dry sandy soil) and Hard paved (Granite)	Vegetation on the periphery of the boundaries	2km	Fully exposed to all climatic variables
Study area D- (Kampa Bhupa's Path)	Soft paved (Sandy soil) and Hard paved (Granite)	Scattered vegetation	50m	Partially exposed to all climatic variables and presence of granite blouders

Microclimate Measurement

We measured the microclimatic conditions of the World Heritage Site in Hampi at four locations on four sunny days from November 2nd to 5th, 2023. Survey days exhibit a maximum daily T_a of about 30°C, with clear skies, no precipitation, and intense solar radiation. We chose measurement locations which are famous attractions in Hampi: a) Study area A (Hampi bazaar street in front of Virupaksha temple), b) Study area B (Vittala bazaar street in front of Vittala temple), c) Study area C (Royal Centre) and d) Study area D (Kampa Bhupa's path along Tungabhadra river) (Figure 1).

We employed Testo 645 (Temperature and Humidity probe), Testo 625 (thermal flow probe), and Testo 480 with (Globe probe Ø 150mm, TC Type K) to obtain microclimate measurements of air temperature (T_a), Relative Humidity (RH), Wind speed (V_a), and Globe Temperature (T_g) at a height of 1.2-1.5 m above ground level. We set the instruments at least 15 minutes before the measurement was recorded, to allow the sensors to stabilise to the ambient conditions. We recorded these microclimate parameters at 30-minute intervals. All the instruments and sensors (Figure 3) have a measuring range and accuracy that comply with the International Organisation for Standardisation (ISO) 7726 standards (Ergonomics of the Thermal Environment-Instruments for Measuring Physical Quantities, 1998).

Table 2. Instruments and sensors used for collecting microclimate data

Meteorological data	Instrument	Measuring Range	Accuracy/Resolution
T_a (°C)	Testo 645 (Temperature probe)	-20 to +70 °C	±0.4 °C (+0.1 to +50 °C)
RH (%)	Testo 645 (Humidity probe)	0 to +100 % RH	±2 %RH (+2... +98 %RH)
V_a (m/s)	Testo 425 (Thermal flow probe)	0 to +20 m/s	±(0.03 m/s +5% of m.v.), 0.01 m/s

T_g (°C)	Testo 480 (Globe probe Ø 150mm, TC Type K)	0 to +50 °C	±0.1 °C, 0.01°C

Figure 3. Instruments and sensors used in the study

We calculated T_{mrt} according to Thorsson et al. (2007) from the measured data of T_a, T_g, and V_a:

$$Tmrt = \left[(Ta + 273.15)^4 + \frac{1.1 \cdot 10^8 \cdot v^{0.6}}{\varepsilon \cdot D^{0.4}} \cdot (tg - ta)\right] 1/4$$

Where *D* is the globe diameter in mm and *ε* is globe emissivity.

We employed the RayMan model to calculate the Universal Thermal Climate Index (UTCI) using the T_{mrt} values (Błazejczyk et al., 2013; Matzarakis et al., 2007). Numerous studies have utilised RayMan for calculating UTCI across various climatic conditions, particularly those focused on hot and semi-arid climates (Dhariwal et al., 2019; Kumar & Sharma, 2022a, 2022b; Su et al., 2024). This encouraged us to use RayMan as an appropriate model and UTCI as thermal comfort indices for our current research. According to Bröde et al. (2012), UTCI can be defined as "the air temperature of the reference conditions causing the same model response as actual conditions." The input provided in the RayMan software included date, time, location, microclimate data, and personal details of the respondents, such as age, gender, clothing, and metabolic rate (Matzarakis et al., 2010). The thermal stress categories of UTCI can be seen in Table 3.

Table 3. UTCI ranges and thermal stress categories

UTCI range	Thermal stress categories
Above 46°C	Extreme heat stress
38 to 46°C	Very strong heat stress
32 to 38°C	Strong heat stress
26 to 32°C	Moderate heat stress
9 to 26°C	No thermal stress
9 to 0°C	Slight cold stress
0 to -13°C	Moderate cold stress
-13 to -27°C	Strong cold stress
-27 to -40°C	Very strong cold stress
Below -40°C	Extreme cold stress

Questionnaire Survey

Subjective parameters, such as personal and physiological factors (age, gender, activity, clothing, position, exposure to sunlight, etc.), are collected through a questionnaire survey and photographic analysis.

The survey was conducted during peak hours, from 10:00 AM to 2:00 PM, over four days in November 2023. We collected photographs for photographic analysis. The target population was all visitors to Hampi. A simple random sampling technique was used to select samples. However, visitors are not directly involved in photographic analysis; the researchers do not contact them. The main aim is to map the users' spatial and behavioural patterns through visual methods (photographs) without interfering with real-life situations.

We collected 160 questionnaires during the questionnaire survey across the four study areas. The survey locations are predetermined based on the visitor's path towards the monuments. The questionnaire was prepared based on the existing research on outdoor thermal comfort (Nikolopoulou et al., 2001; Nikolopoulou & Lykoudis, 2006). Each questionnaire consisted of 20 closed-ended questions, taking 5-8 minutes to complete. According to thermal comfort standards ISO 7730 (ISO, 2005), we structured the questions and used the ASHRAE seven-point scale to interpret the thermal sensation vote. The questionnaire consisted of three sections: thermal comfort judgment scales, visitor responses to materials and vegetation, and preferred adaptation strategies for thermal comfort.

Photographic analysis

Shooshtarian (2019) stated that applying different theories can contribute to the development of more effective and innovative assessment methods to yield valid results. According to semiotic analysis theory, researchers analyse photographs on two levels: denotations and connotations within photographs (Langmann & Pick, 2017). The first level deals with the immediate meaning of the photograph (Aiello, 2006), and the second level interprets the photographs in a more abstract sense (Pennington, 2017).

Penn (2000) provided a detailed guideline for semiotic analysis using photographs. In the first step of this method, the researchers should choose the photographs to have a representative sample (going for quantity). However, selecting purposeful images to convey meaning (going for quality). Secondly, the researcher must denote the photographs. Thirdly, the connotations in the photographs are identified, and finally, the research questions are answered.

We collected the photographs on the same day during the microclimate measurement and questionnaire survey. A high-quality camera captured the real-time scenario in a standing eye-level position. The viewing angles primarily included pedestrian areas connecting the iconic monuments, with more relevant signs highlighting spatial and behavioural features. We chose two photographs from each location. We took one photograph at 10:00 AM and another at 12:00 PM to depict the peak hours of tourist visits. One set of researchers took the photographs, while others took surveys and microclimate measurements. Respondents who took part in the survey were not involved in the photographs. We took the photographs without involving the visitors to record the actual behavioural patterns and adaptation strategies.

We denoted the photographs with spatial and behavioural signs; further detailed connotations were made for each photograph. The parameters selected for the photographic analysis are primarily divided into two categories: spatial and behavioural. These main categories were further subdivided into subcategories. Spatial categories include vegetation, light, shade, and colour, as well as water, furniture, paving, and the sky view factor. Meanwhile, behavioural categories encompass posture and expression, position, motion, and accessories used. We followed Cortesão et al. (2020) for selecting the parameters and categorization of the signs (Cortesão et al., 2020). Respondents' votes on the judgmental scale (thermal sensation, overall thermal comfort, and satisfaction level) were recorded on paper. The recorded responses in the questionnaire survey were verified through photographic analysis, which was used as a qualitative method to assess the thermal environment.

We also employed photographic analysis as a visual method to validate the findings from the questionnaire survey, specifically the information respondents provided about a particular thermal environment. A few standard questions about outdoor thermal experiences can reasonably interpret the thermal condition of a space. However, analyzing these random photographs of the same place would help identify thermal comfort issues and enable the researcher to analyse the people's votes, confirming their reliability. Therefore, we intended the photographic analysis to add to verbal responses and enrich interpretations. We employed this method along with a field survey to verify certain assumptions related to the thermal comfort of the respondents.

Results

The microclimate characteristics

We conducted microclimate measurements in all four study areas during the winter. The following parameters were measured on-site: Air Temperature (T_a), Relative Humidity (RH), Wind Speed (V_a), and Globe Temperature (T_g). Mean Radiant Temperature (T_{mrt}) was calculated using RayMan. In study areas A and C, the average T_a during the survey was 31.68°C, and the average RH, V_a, and T_{mrt} were 54.57%, 0.9 m/s, and 51.5°C, respectively. In study areas B and D, the average T_a during the survey was 30.7°C, the average V_a was 1.5 m/s, and the average T_{mrt} was 49.3°C. However, there is a difference in relative humidity (RH) between study areas B and D. The average RH recorded in study areas B and D was 54.4% and 60.73%, respectively. It is worth noting that due to overcast and windy conditions in study areas B and D during the survey days, T_{mrt} was significantly lower than in study areas A and C. The maximum recorded T_a during the survey was 32.9°C at study area A, while the minimum recorded T_a was 29.2°C. The maximum and minimum T_a show a range of 3°C.

The average UTCI for the study areas ranged from 32°C to 39°C (μUTCI = 36.24°C). Figure 4 shows the hourly variation in average UTCI across all the study areas from 10:00 am to 4:00 pm. Study areas A and C reported high UTCI throughout the day, ranging from 35.3°C to 39.1°C. Study areas B and D reported high UTCI values ranging from 35.6°C to 38.4°C during the mid-afternoon hours.

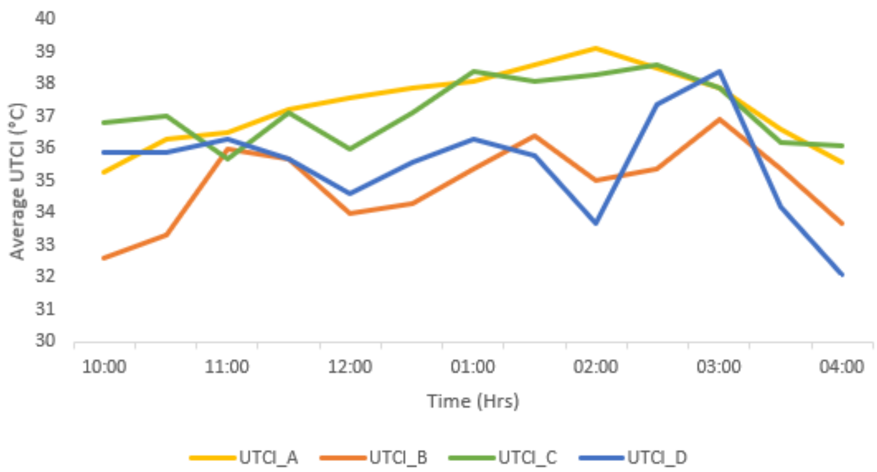

Figure 4. UTCI variations across sampled locations in Hampi

Questionnaire survey results

The questionnaire was distributed to the visitors in all the study areas. A total of 160 questionnaires were completed in four days. A total of 40 questionnaires were completed in each location from morning to afternoon.

In general, respondents consisted of 53.75% males and 46.25% females. The questionnaires were completed by 122 domestic visitors (76.25%) and 38 foreign visitors (23.75%). Most foreign visitors (84.2%) are from European countries, including Spain, France, Germany, the U.K., and Switzerland. Domestic visitors were 36% from Karnataka, 21% from Maharashtra, and 12% from West Bengal. Regarding age, 54.3% of visitors are aged 25-44 years, followed by those aged 45-64 years.

Thermal comfort sensation and satisfaction of tourists

Despite the questionnaire survey being completed in November (one of the cooler months), the thermal sensation vote (TSV) of the visitors is more inclined to the warmer range. The frequency distribution of thermal sensation is shown in Figure 5. Their preference for a cooler environment increased as the feeling of warmth intensified. However, about 43.1% of visitors were satisfied, 31.25% were slightly satisfied, and 3% were very satisfied with the thermal condition. Figure 5 shows the percentage of visitors' satisfaction.

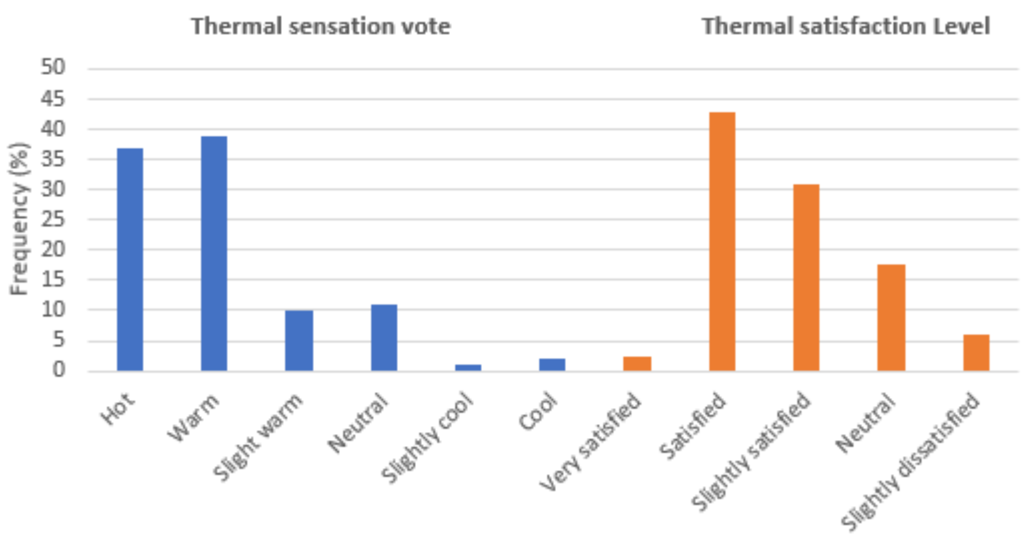

Figure 5. Frequency distribution of Thermal sensation vote and Thermal satisfaction level

Percentage distributions of satisfaction at each study area
The percentage distribution of satisfaction in each study area is shown in Figure 6. The study reveals that areas A, B, and D have the highest satisfaction percentages, while area C has the lowest percentage. The highest neutral percentage belongs to study areas A and C, with 20-22%. Study area C (Royal Centre) scored the lowest level of thermal satisfaction, despite having more trees and a larger grass surface. Trees present in study area C are in the periphery of the site, which does not provide suitable shade in the walkways.

Thermal comfort of visitors
60% of the visitors perceived this thermal condition as comfortable, while 40% voted neutral (Figure 7). In the present study, UTCI values ranged from 33.3°C to 39.1°C in winter. In hot and arid climates, UTCI values ranging from 35.6 to 43.2°C are considered to be under intense heat stress in Indian cities (Kumar & Sharma, 2022a). It is important to note that only 10% of the visitors voted for neutral sensation in winter. This lower percentage of neutral sensation can be due to visitors from different countries residing in different climates participating in this survey. Foreign visitors from various climate zones, such as Russia, Australia, and Norway, tend to prefer warmer environments.

In further questions, visitors were asked about their preferred adaptation strategies. 60% of the visitors prefer to "move to shade/tree," while 25% prefer to get more drinks. However, 80% of visitors also found that the study areas had significantly less greenery and vegetation. Overall comfort (OC) was correlated with the thermal sensation vote (Figure 8). The overall data sets were separated according to the TSV and its corresponding OC responses. The mean values of each data set of OC and TSV were calculated. Furthermore, a correlation was established and is observable in Figure 8.

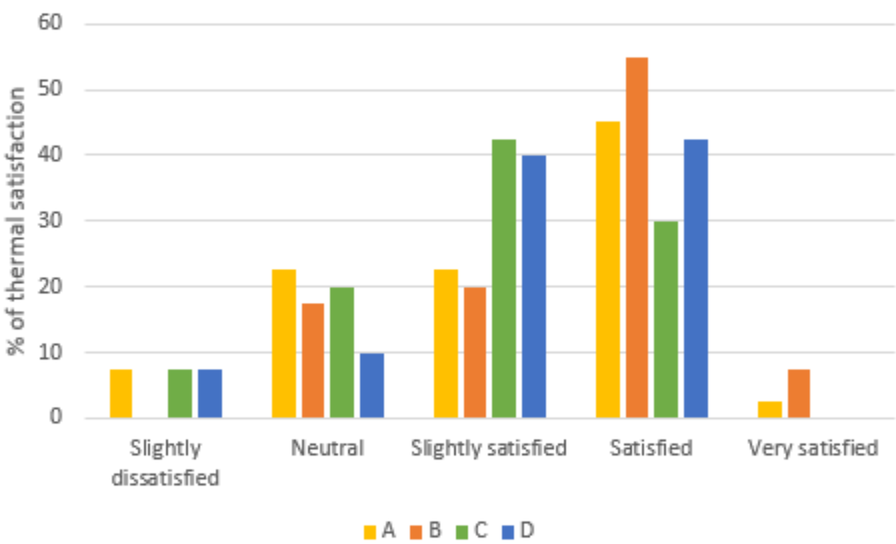

Figure 6. The percentage distributions of satisfaction at each study area

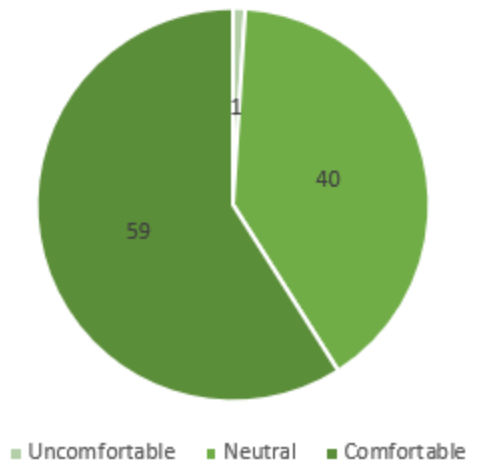

Figure 7. Frequency distribution of Overall comfort vote

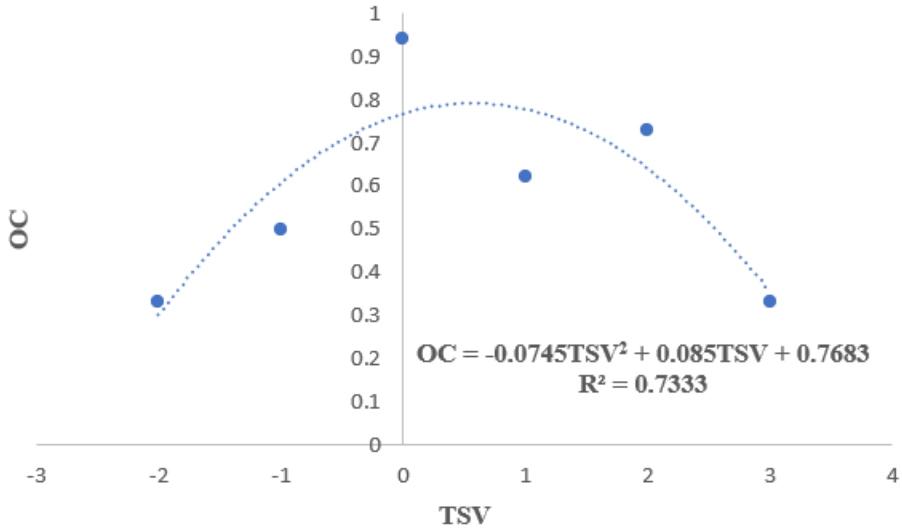

Figure 7. Correlation between the Overall comfort and Thermal sensation vote

Results of Photographic Analysis

In study area A (Figure 9, A1 and A2), a few deciduous trees provide shade where visitors seek shelter from intense solar radiation. Visitors are relaxed under the shade of trees, while those in exposed areas walk quickly. The use of caps, sunglasses, and scarves has also been noticed as an adaptation strategy. Study area B (Figure 9, B1 and B2) shows the walkway and entrance leading to the Vittala Temple. Very few deciduous trees can be seen along with dusty paving. This unshaded walkway is causing discomfort in the area. Visitors are observed in an active posture and walking quickly in the exposed area. Similar to the previous area, hats, caps, and sunglasses were used.

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Figure 8. Photographs of study areas A and B
Source: Authors

Trees, lawns, and hedges are predominant in study area C (Figure 10, C1 and C2) in the Royal Centre. However, tree shade is not present on the walkways. Visitors are often seen walking under the exposed sun, employing adaptation strategies such as umbrellas and scarves. Visitors are seeking shelter near the shaded areas. Study area D (Figure 10, D1 and D2) is along the river, and boulders can be seen in the photographs. There is no shade from trees over the walkway. However, visitors are sheltering under the shade in a relaxed position. The use of caps, hats, and sunglasses is also seen in this photograph.

Figure 9. Photographs of study areas C and D
Source: Authors

Table 4 summarizes the key signs observed in the photographic analysis. Exposed trunk, glare, dusty paving, clear sky vault, fast walking, and squinting are signs of thermal discomfort in all the study areas.

Table 4. Summary of the key signs observed in the photographic analysis

Category	**Subcategory**	**Photograph of Study Area A**	**Photograph of Study Area B**	**Photograph of Study Area C**	**Photograph of Study Area D**
Spatial	Vegetation	Trees	Nominal trees	Trees on periphery, lawn and hedges	Trees and Bushes
	Light, shade and colour	Bright canopy, Cool colour	Dark boulders	Bright canopy, Cool colour	Bright canopy, Cool colour Dark boulders
	Water	-	-	-	Moving water
	Furniture	Stone benches	-	-	Stone benches
	Paving	Hard (Concrete)	Dusty	Dusty	Hard (Granite)

	Sky view factor	Clear sky vault	Clear sky vault	No sky vault	Clear sky vault
Behavioural	Posture and Expression	Active posture, Relaxed posture under tree shade	Active posture, Squinting	Active posture	Relaxed posture under tree shade
	Position	People walking under exposed sun, people sheltering under shade	People walking under exposed sun	People walking under exposed sun as well as people sheltering under shade	People sheltering under tree
	Motion	Fast walking, standing under shade	Fast walking	Both slow and fast walking	Slow walking
	Accessories	Cap, sunglasses, scarf	Hat, cap, sunglasses	Hat, cap, umbrella, scarf	Hat, sunglasses

Based on the visual signs of the photographs, 6 out of 12 signs convey thermal comfort, and the other six signs convey thermal discomfort in study areas A, C, and D. In photographs at study area B, all eight signs of thermal discomfort are conveyed. Most signs of thermal discomfort are related to direct, intense solar radiation and the absence of shade. This finding suggests that intense solar radiation in this climatic region is the leading cause of thermal discomfort. Furthermore, 62.5% of visitors also reported that solar radiation was intense during the survey, which made them uncomfortable. This argument aligns with existing studies that indicate exposure to direct solar radiation is the primary cause of thermal discomfort in outdoor spaces (Zhao et al., 2023; Ji et al., 2022).

Discussion

The study was conducted in Hampi, a World Heritage Site, which has a hot and semi-arid climate. This study analyses the outdoor thermal comfort conditions in the peak season through microclimate measurements, questionnaire survey, and photographic analysis, as a pilot study conducted during the winter of 2023. The results show that, despite being in the winter season, the thermal condition of the heritage is not significantly comfortable. The UTCI across the study areas in Hampi ranged from 33.3°C to 39.1°C during the field survey, similar to other studies in Bsh cities in India (Kumar & Sharma, 2022a, 2022b, 2022c). There is variation in UTCI values between the study areas, which can be attributed to the overcast, windy conditions during the survey period. Hence, the thermal conditions of the study areas can be considered the same. Visitors feel warmer during the high tourism season in November and prefer to be cooler despite winter. The calculated UTCI range during the survey is higher than the conventional UTCI neutral range in the Bsh climate, which typically ranges from 28.03 to 35.6°C. Notably, the neutral UTCI was 31.8°C in the summer season (Kumar & Sharma, 2022a).

This research also reports that, despite the heat stress in Hampi, 77% of the visitors are satisfied with the existing thermal conditions. Various authors report similar findings for tourism context studies where 78.57% and 50-60% of tourists were satisfied with the thermal conditions in Isfahan and Sevilla, Madrid, respectively (Karimi & Mohammad, 2022; Nasrollahi et al., 2017). This shows that the tourists are psychologically compatible with the thermal conditions of the tourist sites.

Photographic analysis reveals the signs of thermal comfort and discomfort in the spatial and behavioural categories. Exposed trunk, glare, dusty paving, clear sky vault, fast walking, and squinting are signs of thermal discomfort in all the study areas. However, few signs of thermal comfort are observed in all study areas, except for study area B, which includes relaxing in a posture under tree shade and slow walking on shaded pathways. These signs of thermal comfort and discomfort are under study (Cortesão et al., 2020). Visitors are often found seeking shade under trees in study areas A and D. This is in line with other studies in India, where visitors also seek shade under trees and overhead canopies; however, the availability of shade depends on the specific location (Manavvi & Rajasekar, 2020).

It is essential to note that visitors are generally satisfied with the existing thermal conditions; however, the spatial and behavioral patterns of the visitors are inconsistent with the results of the questionnaire survey and microclimatic measurements. This indicates the psychological compatibility and adaptation behaviour of the visitors. This finding aligns with the results of various studies in the tourism context (Karimi & Mohammad, 2022; Nasrollahi et al., 2017).

Simulation, microclimatic measurements, and questionnaire surveys can predict thermal comfort conditions. However, photographic analysis can complement conventional methods. Results from the questionnaire survey can be biased due to the visitors' mental adaptability and adaptation measures. Hence, this qualitative approach through photographic analysis can further validate or complement the findings from the questionnaire survey.

Photographic analysis can help researchers communicate the findings as visual guidelines to designers and planners. These visuals can help designers consider more climate-responsive designs. Photographic analysis can further help them to represent the thermal environment and improve the microclimate of a site. Visual signs in the photographs can help the researcher understand the relationship between spatial and behavioural patterns of visitors and thermal comfort or discomfort. These visual signs work together to assess the microclimatic condition. These visual signs are subjective. However, the researchers cannot control the behaviour-related signs. Thus, the thermal message is more realistic in photographic analysis, where the respondents are not directly involved.

The research has several limitations and offers some future perspectives for further investigation. Firstly, the present study was conducted only during the winter season; however, research work should also be carried out during the summer season. Secondly, a neutral UTCI could not be calculated since the variability in T_a was not large enough to determine a neutral temperature for the samples. Furthermore, intangible cultural aspects of the study have not been taken into consideration.

Conclusion

This research presents a preliminary approach to using photographic analysis as a qualitative method to assess the existing thermal environment in the World Heritage Site of Hampi, India. Outdoor thermal comfort was explored using microclimate measurements and questionnaire surveys. The proposed methodology enabled the exploration of existing thermal conditions in a heritage site using a qualitative approach in addition to conventional methods. This research is the first study to assess outdoor thermal comfort for visitors to the heritage site of Hampi. In the tourism context, the responses on the judgmental scales can be biased due to the visitors' psychological compatibility and adaptation measures. Therefore, the main focus of the study is to assess the outdoor thermal environment of the heritage site using the theory of semiotic analysis. The conclusions from this research are as follows:

[1] The average UTCI calculated for the study areas varied between 32°C and 39°C, with an average of 36.24°C, which corresponds to "strong heat stress."

[2] The majority of visitors experienced thermal sensations ranging from "warm" to "hot" during the winter season in a hot and semi-arid climate. It suggests that the existing thermal conditions of the heritage site are not very comfortable for visitors.

[3] Despite the study area experiencing strong heat stress and visitors feeling hot and warm, the majority of the visitors are satisfied with the thermal conditions of the heritage site. However, the overall comfort of the visitors correlates well with the thermal sensation votes.

[4] The most common signs of thermal discomfort are mostly related to intense solar radiation and the absence of shade. Thus, indicating the need for more shaded areas.

[5] We report an inconsistency in results between photographic analysis and the overall comfort vote of the visitors. Thus, photographic analysis can further validate the findings from the questionnaire survey. However, photographic analysis can be complemented by conventional approaches.

This approach can help researchers identify hotspots, determine suitable locations for the weather station, and identify feasible locations for the questionnaire survey. We can use this approach in other contextual studies to assess the thermal environment as a preliminary survey. This study's findings can help enhance the outdoor environment during peak tourist season. However, we can also utilise this framework during the low tourist season to further increase tourist footfall and enhance the visitors' experience. Results will help formulate heat stress mitigation strategies for visitors to World Heritage Sites, aiming to increase visitor numbers. The results can further guide the designers and decision-makers in World Heritage Sites in identifying the key signs of thermal comfort and discomfort for future preservation and management of heritage sites.

List of abbreviations

ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers, ISO – International Organization for Standardization, ICOMOS – The International Council on Monuments and Sites, PET – Physiologically Equivalent Temperature, RH – Relative Humidity, T_a – Air Temperature, T_g – Globe Temperature, T_{mrt} – Mean Radiant Temperature, UTCI – Universal Thermal Climate Index , V_a – Wind Speed, WHS – World Heritage Site

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Extreme precipitation events in Novi Sad during the period 1961-2020

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Abstract

Extreme precipitation events (EXPEs) were analyzed based on daily precipitation data from 1961 to 2020 in Novi Sad, Serbia. The temporal characteristics of the following EXPEs were investigated: Heavy precipitation days (R10mm), Very heavy precipitation days (R20mm), Highest 1-day precipitation amount (Rx1day), Highest 3-day precipitation amount (Rx3day), Highest 5-day precipitation amount (Rx5day), Very wet days (R95p), Extremely wet days (R99p), Precipitation fraction due to very wet days (R95pTot) and Precipitation fraction due to extremely wet days (R99pTot). The EXPEs were analyzed on an annual and seasonal basis and for two reference periods 1961-1990 and 1991-2020. Positive trends were found for both annual and seasonal values for all indices, except for R20mm and R99pTot in winter. A significant increase in Rx1day, Rx3day and Rx5day was observed in all seasons (except for Rx1day and Rx5day in winter) and on an annual basis. The high value of Rx1day (116.6 mm) was recorded in the summer of 2018 in Novi Sad, caused by convective precipitation that led to urban flooding. The possible influence of large-scale circulation patterns was investigated. A strong positive and negative influence of the East Atlantic pattern and the East Atlantic Western Russia pattern on the EXPEs was found. The results of this work support the growing evidence that the impact of extreme conditions is likely to become even stronger due to changes in their intensity and frequency.

Keywords: extreme precipitation events; precipitation indices; Novi Sad; Serbia

Introduction

The risk of extreme precipitation events is increasing due to global warming (e.g. Fuentes-Franco et al., 2023). It is known that a warmer atmosphere can hold more moisture (Zeder & Fisher, 2020). According to the Clausius-Clapeyron relationship, the intensity of daily extreme precipitation increases by about 7 % per ºC temperature (Trenberth, 1999). There is a high confidence that extreme precipitation will increase with climate change (IPCC, 2021). A significant increase in heavy rainfall events has been observed worldwide, both on a continental and global scale (Westra et al., 2013; Sun et al., 2021) and on a regional scale (Wang et al., 2014). Van den Besselaar et al. (2013) found that five-, ten- and twenty-year

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events with 1-day and 5-day precipitation became more frequent in Europe in the period 1951–2010. Zeder and Fischer (2020) pointed out that extreme precipitation increased at the majority of stations in Central Europe in the period 1901-2013. Based on the daily precipitation from 40 regional climate simulations of the EURO-CORDEX ensemble, Ettrichrätz et al. (2023) found a significant increase in heavy and extreme precipitation in Central, Northern and Eastern Europe. Extreme precipitation can lead to flooding (Berényi et al., 2023), soil erosion (Eekhout & de Vente, 2022), and landslides (Gariano & Guzzetti, 2016). Successful mitigation of these damages depends on the prediction of extreme rainfall events and better design and planning of urban drainage systems (Zhou et al., 2017; Davis & Naumann, 2017). Characterization of heavy rainfall events in urban areas is the first line of defense against urban flooding and crucial for risk management.

Serbia is a continental country in south-eastern Europe, located in the western region of the Balkan Peninsula. The northern part of the country is characterized by low elevation, which gradually rises towards the southern parts which are covered by mountains and hills surrounding river valleys. The climate of Serbia varies spatially from a temperate continental climate in the northern part to a continental climate in the central part and a modified Mediterranean climate in the southern part (Bajat et al., 2015). The average annual temperature in the lowlands is between 11 and 13 °C, while the average annual temperature in the mountains is below 8 °C. The mean annual precipitation is between 500 and 700 mm in the lowlands and over 1000 mm in the mountains (Vujadinović Mandić et al., 2022). The northern part of Serbia is the administrative unit of the Autonomous Province of Vojvodina, which is the most important agricultural region in the country. Agriculture is one of the most important sectors of the Serbian economy, and the factors that influence agriculture, especially climate conditions, have an impact on the economy of the entire country. Extreme weather conditions such as heavy precipitation affect not only crop production (Milošević et al., 2015; Mimić et al., 2022), but also the well-being of people living in urban areas. There are only a few recent studies that report the results of the analysis of precipitation in Vojvodina. Tošić et al. (2014) investigated the seasonal and annual variability of precipitation (recorded in monthly frequency at 92 stations in the period 1946-2006) in Vojvodina using empirical orthogonal functions (EOF). The trend analysis of the first EOF pattern (PC1) showed an increasing trend for annual, summer and fall precipitation and a decreasing trend for winter and spring precipitation. They indicated that the annual, winter and fall precipitation are influenced by the North Atlantic Oscillation (NAO).

Malinović-Milićević et al. (2018) examined the temporal and spatial variability of extreme precipitation in Vojvodina by analyzing the trends of extreme precipitation indices calculated from daily data from seven stations in the period 1966–2013. The results (based on precipitation magnitude and frequency) indicated that the climate is getting wetter in the northern and central part of the region, while the southernmost part of the region is getting drier, which is consistent with observations from central and southern European regions, respectively.

Bezdan et al. (2024) investigated the impact of climate change on extreme precipitation events and the associated risk of flooding based on the occurrence of the highest 3-day precipitation amount (Rx3day) in spring with a 10 years return period. They compared results from observational data (9 meteorological stations) for the period 1971-2019 with projections from 2020 to 2100 produced with an ensemble of eight regional climate models from the EURO-CORDEX project database. The results show that the Rx3day in spring increases by 19 to 33% with a 10 years return period and the probability of more than one event occurring in which the Rx3day exceeds the threshold values increases by 105.6 % to 200.0 % compared to the historical period. For the future period, the Rx3day values in spring (used for the design of pluvial flood protection systems in Vojvodina) are below the future projections, indicating an increased risk of pluvial flooding.

In this work we focus on the extreme precipitation in the city of Novi Sad, the capital of Vojvodina. Previous studies dealt with the problem of heat waves (Savić et al., 2018) and heat islands (Unger et al., 2011) as well as dynamics of air temperature in the "local climate zones" (Milošević et al., 2022). The main objective of this study is to analyze extreme precipitation events (EXPEs) on an annual and seasonal basis from 1961 to 2020 in Novi Sad. We examined trend on annual and seasonal time series of all analyzed EXPE indices for the entire 60-year period and compared the descriptive statistics for the two 30-year reference periods (1961-1990 and 1991-2020). We also investigate the possible influence of large-scale circulation patterns on extreme precipitation.

Materials and Methods

Study area and data

Novi Sad is the capital of the autonomous province of Vojvodina and the second largest city in Serbia with 335,000 inhabitants and an area of 112 km^2 (Unger et al., 2011). Novi Sad is situated in the northern agricultural lowland region of Serbia, in the south of the Pannonian Plain (Fig. 1). The city center is surrounded by agricultural fields in the north, east and west (with a low elevation of about 80 m), while the southeastern districts of Sremska Kamenica and Petrovaradin are located on higher terrain (up to 130 m) on the edge of the northern slope of Fruška Gora (low mountain range with the highest peak at 539 r). The main watercourse is the Danube, which is 260-680 m wide and flows in the east-west direction in the southern part of the town. The Danube–Tisza–Danube Canal crosses the city from northwest to southeast and separates the industrial area in the north from the urban area in the south. The climate exhibits characteristics of the Cfb-Köppen–Geiger (temperate climate with warm summers and well-distributed precipitation throughout the year) climate type (Milošević et al., 2022). Based on data from 1949 to 2015, the mean annual precipitation is 622.8 mm and the mean monthly temperature ranges from −0.3 °C in January to 21.8 °C in July (Savić et al., 2018).

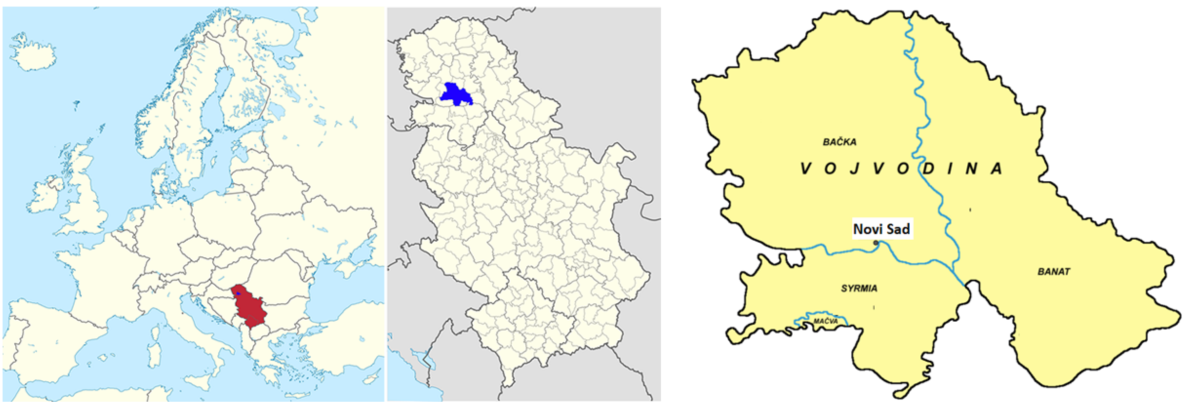


Figure 1. Position of Serbia in Europe (left), position of Novi Sad in Serbia (center), and Vojvodina (right)
Source: https://sco.m.wikipedia.org/wiki/File:Novi_Sad_in_Serbia_and_Europe.png

Extreme precipitation events (EXPEs) were analyzed based on daily precipitation from 1961 to 2020 in Novi Sad, Serbia. The data used in this work includes daily precipitation amounts recorded at the station of Novi Sad (45°20' N; 19°51' E; 84 m altitude) and is provided by the Serbian Meteorological Service, which technically and critically controlled these measurements.

Monthly values of Northern Hemisphere teleconnection patterns (North Atlantic Oscillation - NAO, Eastern Atlantic - EA, and Eastern Atlantic Western Russia - EAWR pattern) were downloaded from the Columbia Climate School (International Research Institute for Climate and Society) https://iridl.ldeo.columbia.edu/SOURCES/.Indices/.CPC_Indices/.NHTI/ for the period 1961–2020.

Methods

Climate indices

The Expert Team on Climate Change Detection and Indices (ETCCDI) has developed a set of 27 indices based on daily temperature and precipitation that are commonly used in climate change analysis (Alexander & Arblaster, 2017; Yin & Sun, 2018; Cooley & Chang, 2021). From this list, 9 indices are selected and presented in Table 1. The temporal characteristics of the following EXPEs were investigated: R10mm (Heavy precipitation days), R20mm (Very heavy precipitation days), Rx1day (Highest 1-day precipitation amount), Rx3day (Highest 3-day precipitation amount), Rx5day (Highest 5-day precipitation amount), R95p (Very wet days), R99p (Extremely wet days), R95pTot (Precipitation fraction due to very wet days) and R99pTot (Precipitation fraction due to extremely wet days). The EXPEs were analyzed on an annual and seasonal basis and for two reference periods 1961-1990 and 1991-2020.

The modified Man-Kendall (MMK) test

In this work we use the Mann-Kendall test modified by effective sample size to detect trends in serially correlated hydrological series, proposed by Yue and Wang (2004). The description of this MMK procedure is presented in (Stosic et al., 2024), and all the calculations are performed using open-source software (Patakamuri & O'Brien, 2021; R Core Team, 2023).

Table 1. Precipitation climate indices with their names, definitions and units

No	Index	Indicator name	Definitions	Unit
1	R10mm	Heavy precipitation days	Number of days where RR (daily precipitation) ≥ 10 mm	days
2	R20mm	Very heavy precipitation days	Number of days where RR ≥ 20 mm	days
3	RX1day	Highest 1-day precipitation amount	The maximum 1-day values for period j	mm
4	RX3day	Highest 3-day precipitation amount	The maximum 3-day values for period j	mm
5	RX5day	Highest 5-day precipitation amount	The maximum 5-day values for period j	mm
6	R95p	Very wet days	Number of days where RR (RR ≥ 1) ≥ 95th percentile	days
7	R99p	Extremely wet days	Number of days where RR (RR ≥ 1) ≥ 99th percentile	days
8	R95pTot	Precipitation fraction due to very wet days	$\text{R95pTot}_j = 100 \frac{\sum RR_{wj}}{RR_j}$, where $RR_{wj} > RR_{wn}95$	%

9	R99pTot	Precipitation fraction due to extremely wet days	$R99pTot_j = 100\frac{\sum RR_{wj}}{RR_j}$, where $RR_{wj} > RR_{wn}99$	%

The large-scale teleconnection patterns (LSTP)

The following teleconnection patterns, the North Atlantic Oscillation (NAO), East Atlantic pattern (EA) and East Atlantic Western Russia (EAWR) pattern are considered to investigate possible influence of the LSTP on EXPEs. The NAO consists of two centers of action being located near Iceland and the Azores and has a positive correlation with precipitation in Northern and Western Europe, and a negative one over Southern Europe, including Serbia (Hurrell, 1995). The EA pattern is characterized by two anomaly centers that are displaced southeastward to the approximate nodal lines of the NAO pattern (Barnston & Livezey, 1987). According to Krichak et al. (2014), the EAWR pattern is associated with negative geopotential height anomalies over the North Atlantic and the area north of the Caspian Sea and positive geopotential height anomalies over Western Europe and Northern China. Tošić and Putniković (2021) pointed out that precipitation over Serbia is negatively correlated with the EAWR. To examine links between EXPEs and LSTP, the Pearson correlation was used and calculated using the open-source software tool "Scipy", Python library. The Student's *t*-test at the 0.05 significance level was applied to check the significance of correlation.

Results

Seasonal analysis

Heavy precipitation days (R10mm)

Figure 2 shows the seasonal values of heavy precipitation days (R10mm). Looking at all seasons, the highest number of days with more than or equal to 10 mm is recorded in summer. The mean value of R10mm is highest in summer in both periods: 6.3 from 1961 to 1990 and 7.6 from 1991 to 2020 (Table 2). However, the highest R10mm value (21) is observed in spring in the period 1991-2020 (Table 2). All seasonal values increased in the second period, except for the minimum value of R10mm in fall, which was 0 in 2018. The maximum value of R10mm was measured in the spring (21) and summer (19) of 2014 at the Novi Sad station.

Table 2. Minimum, mean and maximum values of R10mm during two periods: 1961-1990 and 1991-2020

R10mm	1961 - 1990			1991 - 2020		
season	**min**	**mean**	**max**	**min**	**mean**	**max**
Winter	0	3.1	10	0	3.7	10
Spring	0	4	10	0	5.7	21
Summer	1	6.3	16	2	7.6	19
Fall	1	4.0	10	0	6.2	13

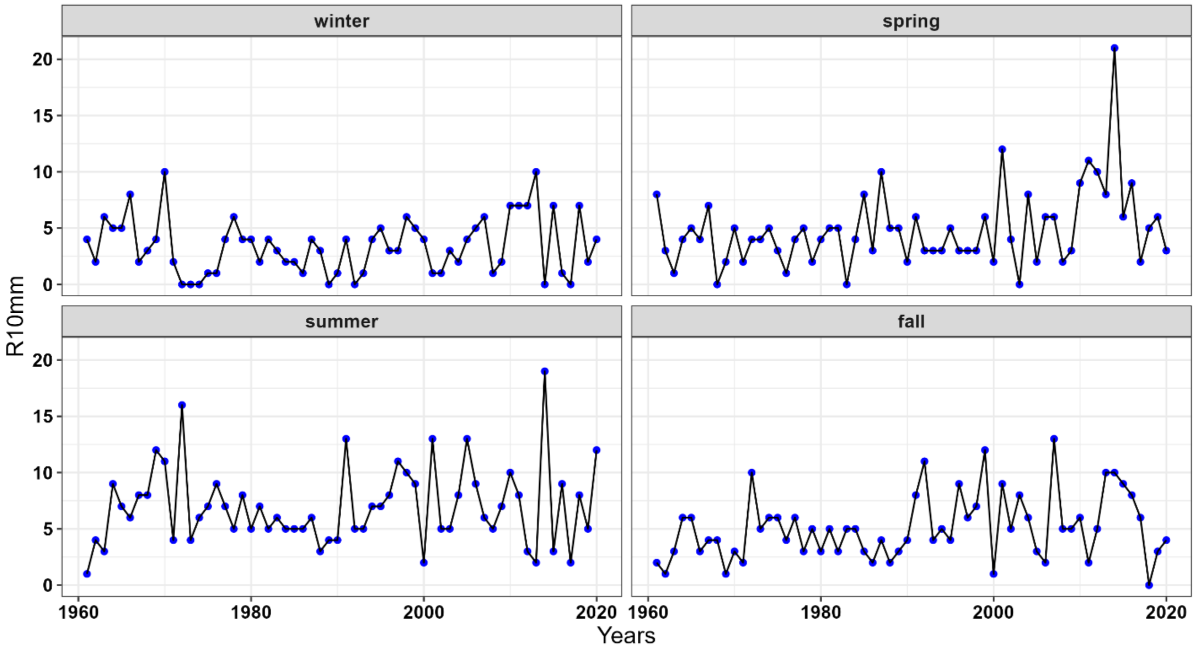


Figure 2. Seasonal values of R10mm during the period 1961-2020 in Novi Sad

Very heavy precipitation days (R20mm)

The seasonal values of very heavy precipitation days (R20mm) are shown in Fig. 3. There was a low number of R20mm in all seasons except summer (Fig. 3). The lowest number of heavy precipitation days was recorded in winter. The mean value of R20mm was 0.4 from 1961 to 1990 and 0.5 from 1991 to 2020 (Table 3). On the other hand, the mean value of R20mm was 2.4 from 1961 to 1990 and 3.2 during the second period in summer, with a maximum value of 9 and 8.

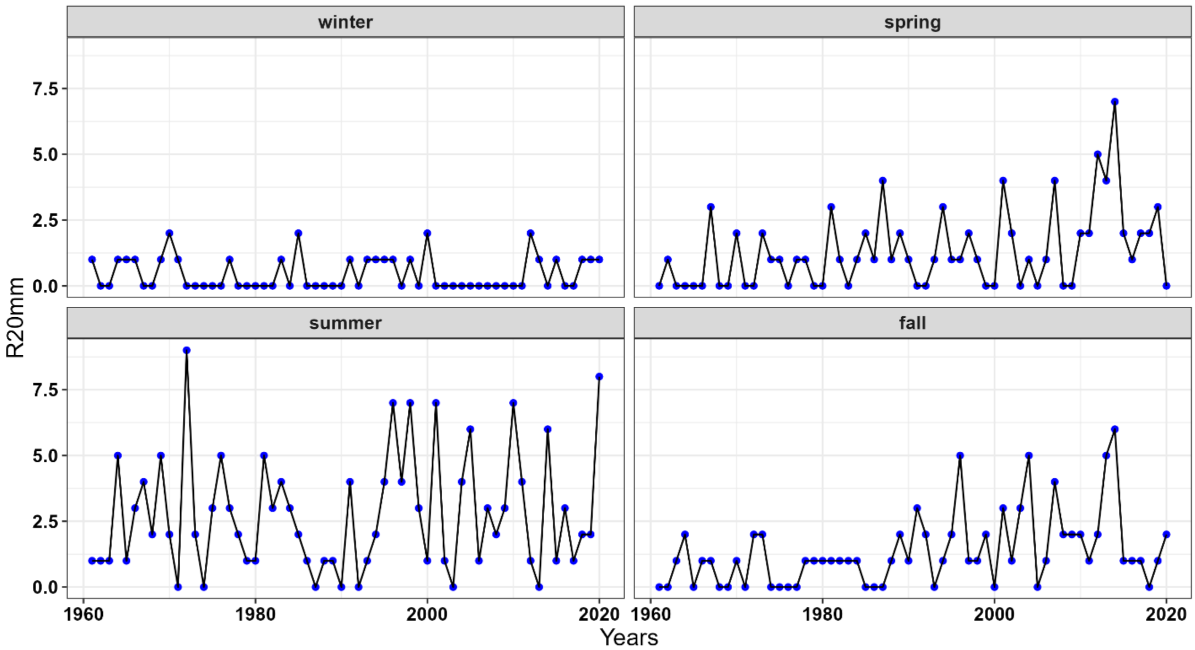


Figure 3. Seasonal values of R20mm during the period 1961-2020 in Novi Sad

Table 3. Minimum, mean and maximum values of R20mm during two periods: 1961-1990 and 1991-2020

R20mm	1961 - 1990			1991 - 2020		
season	**min**	**mean**	**max**	**min**	**mean**	**max**
Winter	0	0.4	2	0	0.5	2
Spring	0	0.9	4	0	1.7	7
Summer	0	2.4	9	0	3.2	8
Fall	0	0.7	2	0	2	6

Highest 1-day precipitation amount (Rx1day)

Figure 4 shows the seasonal values of the highest 1-day precipitation amount (Rx1day). Daily precipitation was below 40 mm in winter and below 70 mm in fall (Fig. 4). There were two peaks for Rx1day in spring, 121.9 mm in 2015 and 91.8 mm in 1987. The highest 1-day precipitation values were measured in summer (Fig. 4). The mean values of Rx1day were highest during the summer season in both periods considered, 33.7 in the first and 44.5 in the second period (Table 4). All descriptive statistics increased in the second period 1991-2020, except for the mean and peak in winter (Table 4).

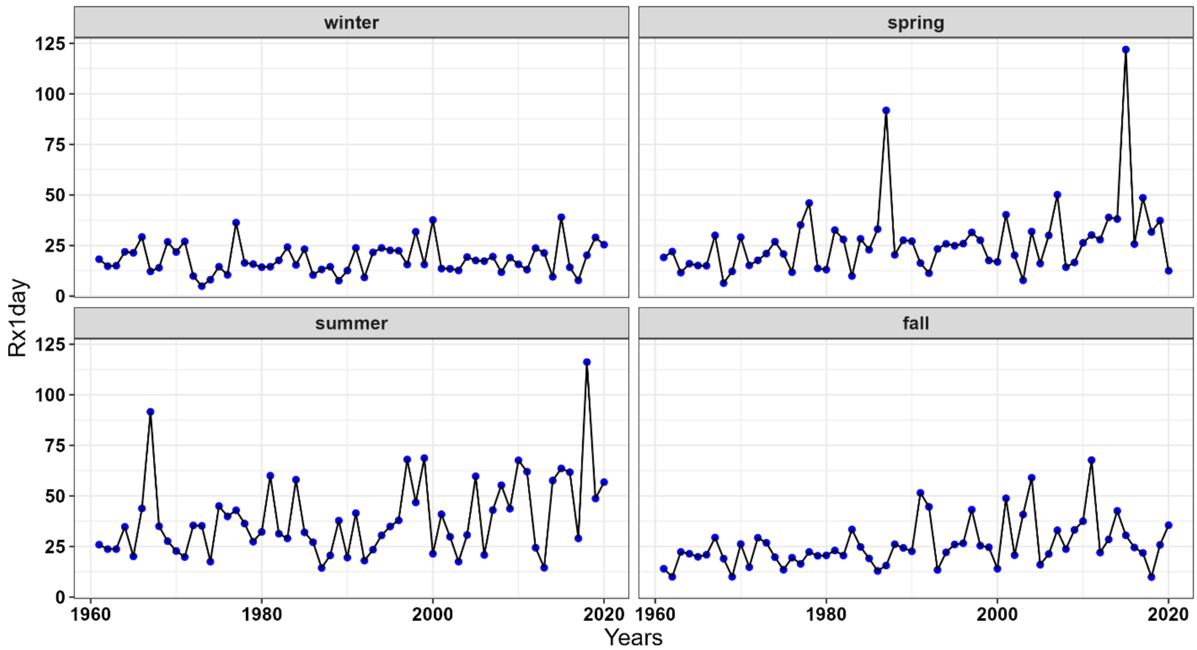


Figure 4. Seasonal values of Rx1day during the period 1961-2020 in Novi Sad

Table 4. Minimum, mean and maximum values of Rx1day during two periods: 1961-1990 and 1991-2020

Rx1day	1961 - 1990			1991 - 2020		
season	**min**	**mean**	**max**	**min**	**mean**	**max**
Winter	4.9	16.9	36.3	7.0	7.8	19.6
Spring	6.4	24.0	91.8	7.8	29.6	121.9
Summer	14.4	33.7	91.6	14.5	44.5	116.2
Fall	10	20.6	33.4	9.9	31.1	67.7

Highest 3-day precipitation amount (Rx3day) and Highest 5-day precipitation amount (Rx5day)

Rx3day and Rx5day are shown in Fig. 5 and Fig. 6 respectively. As in the case of Rx1day, the lowest values of both indices were recorded in winter. Higher values of Rx3day (Fig. 5) and Rx5day (Fig. 6) are recorded in the fall than in the winter. Two maxima can be observed in spring: 149.4 mm in 2015 and 102.6 mm in 1987 for Rx3day (Table 5) and 162.3 mm in 2015 and 104.7 mm in 1987 for Rx5day (Table 6). The minimum, mean and maximum values of both indices increased from 1991 to 2020 compared to 1961-1990, with the exception of the minimum values of Rx3day (Table 5) and Rx5day (Table 6) during the fall season.

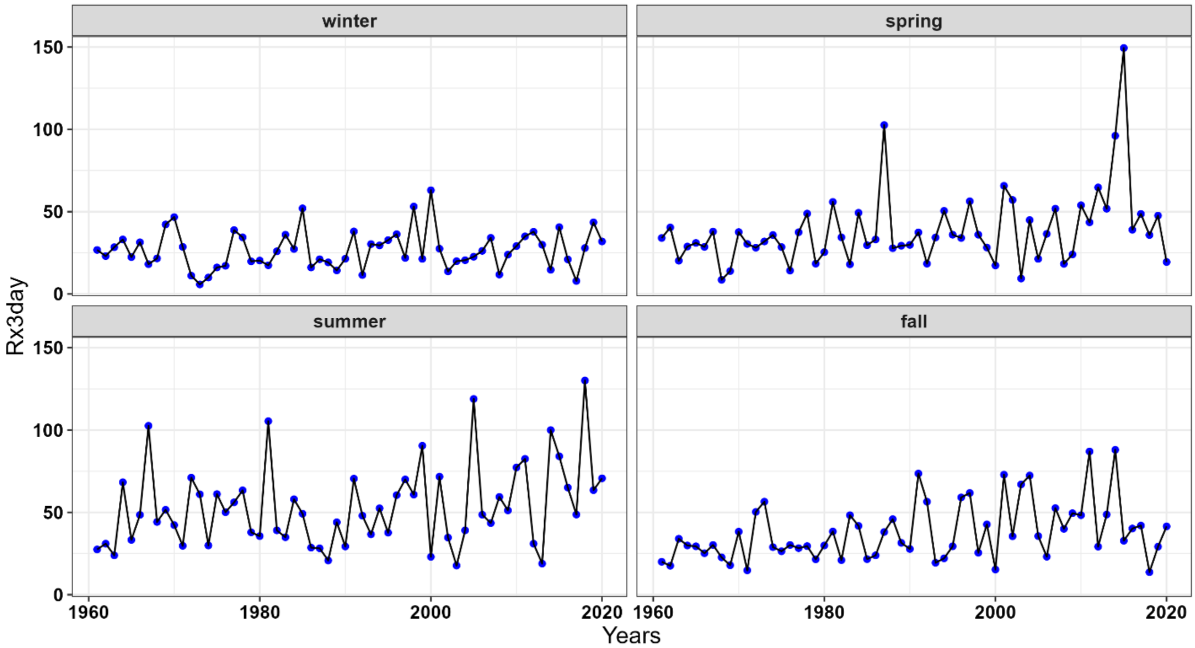


Figure 5. Seasonal values of Rx3day during the period 1961-2020 in Novi Sad

Table 5. Minimum, mean and maximum values of Rx3day during two periods: 1961-1990 and 1991-2020

Rx3day	1961 - 1990			1991 - 2020		
season	**min**	**mean**	**max**	**min**	**mean**	**max**
Winter	5.8	24.9	52	7.9	28.6	63
Spring	8.6	33.0	102.6	9.4	44.2	149.4
Summer	20.8	46.9	105.4	17.7	60.2	130.1
Fall	14.8	30.6	56.5	13.7	45.2	88

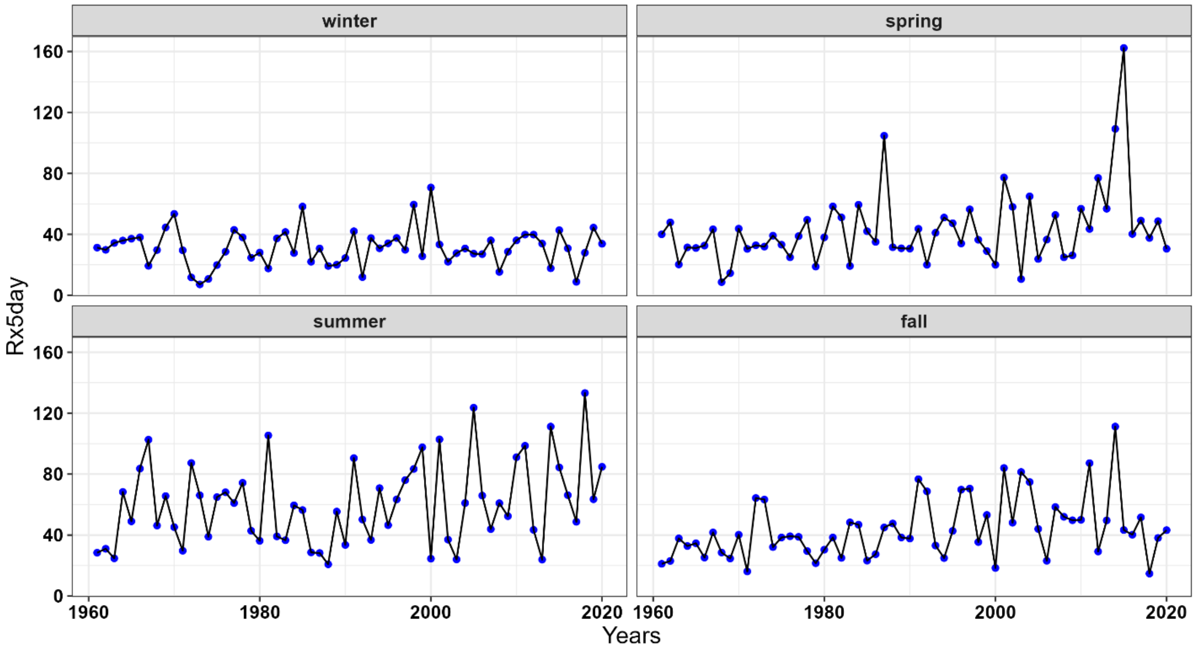


Figure 6. Seasonal values of Rx5day during the period 1961-2020 in Novi Sad

Table 6. Minimum, mean and maximum values of Rx5day during two periods: 1961-1990 and 1991-2020

Rx5day	1961 - 1990			1991 - 2020		
season	**min**	**mean**	**max**	**min**	**mean**	**max**
Winter	7.1	29.8	58.2	8.8	32.8	70.7
Spring	8.6	37.1	104.7	10.6	48.8	162.3
Summer	20.8	52.6	105.4	23.9	68.7	133.2
Fall	16.1	35.4	64.3	14.7	52.2	111.2

Very wet days (R95p)

Very wet days are shown in Fig. 7. The values of R95p were lower than 13 days in all seasons. The only exception was spring 2014, when 19 days were observed in Novi Sad. The descriptive statistics (mean and maximum values) presented in Table 7 show that all seasonal values increased in the period 1991-2020. The highest increase in the maximum value of R95p is observed in the spring, from 9 to 19 in the second period (Table 7).

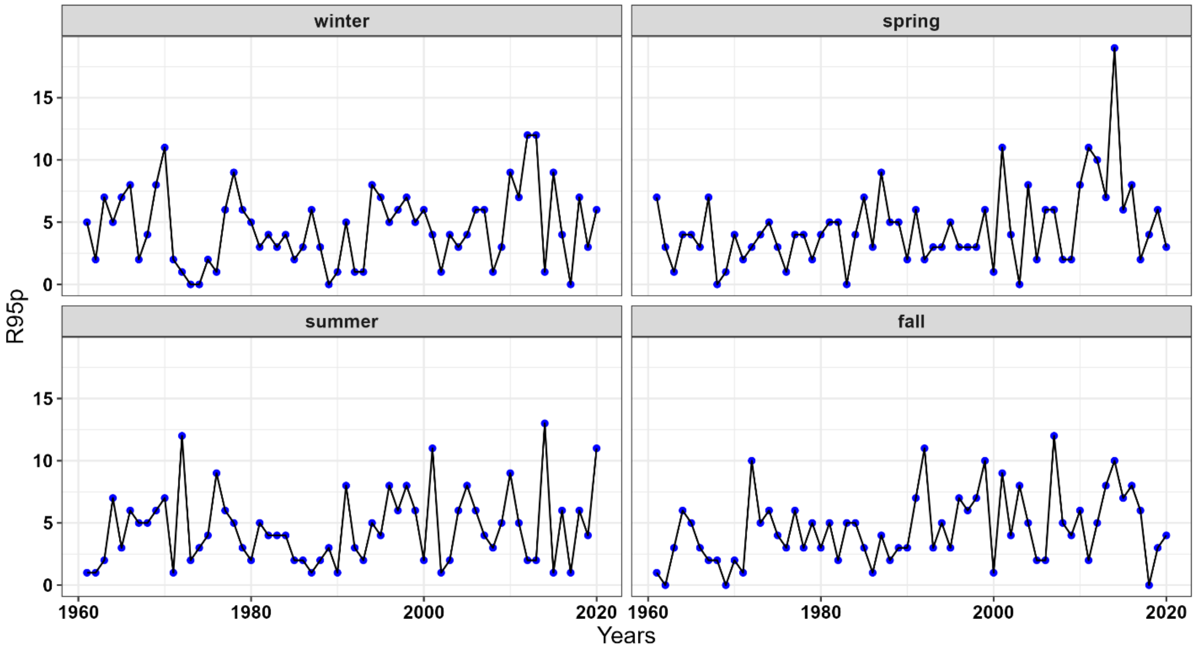


Figure 7. Seasonal values of R95p during the period 1961-2020 in Novi Sad

Table 7. Minimum, mean and maximum values of R95p during two periods: 1961-1990 and 1991-2020

R95p	1961 - 1990			1991 - 2020		
season	**min**	**mean**	**max**	**min**	**mean**	**max**
Winter	0	4	11	0	5.1	12
Spring	0	3.7	9	0	5.3	19
Summer	1	3.9	12	1	5.3	13
Fall	0	3.4	10	0	5.7	12

Extremely wet days (R99p)

The extremely wet days are shown in Fig. 8. In general, the number of days greater than or equal to the 99th percentile was low (less than 3) in all seasons. Five days with R99p were observed in winter (2013) and spring (2014), 7 in summer (2010) and six in fall (2014). Table 8 shows that the mean and maximum values of R99p increased in all seasons. The minimum number of R99p values was zero in the period 1961-2020.

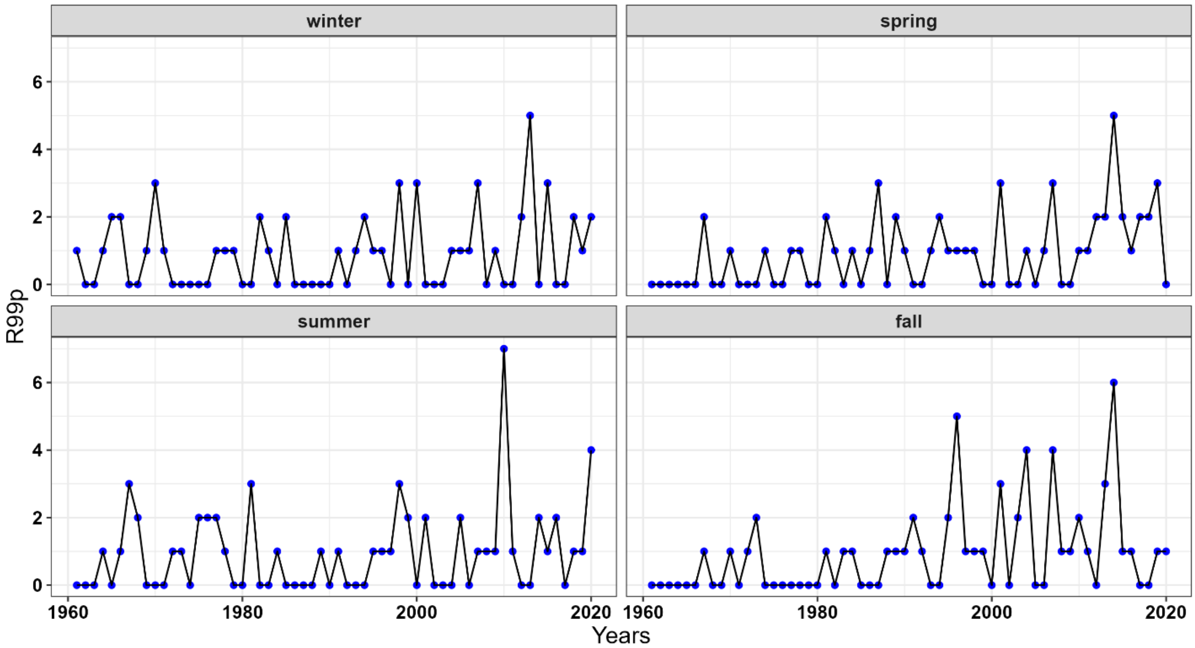


Figure 8. Seasonal values of R99p during the period 1961-2020 in Novi Sad

Table 8. Minimum, mean and maximum values of R99p during two periods: 1961-1990 and 1991-2020

R99p	1961 - 1990			1991 - 2020		
season	**min**	**mean**	**max**	**min**	**mean**	**max**
Winter	0	0.6	3	0	1.1	5
Spring	0	0.6	3	0	1.2	5
Summer	0	0.7	3	0	1.2	7
Fall	0	0.4	2	0	1.5	6

Precipitation fraction due to very wet days (R95pTot)

The seasonal values of precipitation fraction due to very wet days (R95pTot) are shown in Fig. 9. The values of R95pTot increase in all seasons (Fig. 9), as can be seen for the mean and maximum values of R95pTot in Table 9. The highest increase in the mean and maximum values of R95pTot is observed in the fall (Table 9).

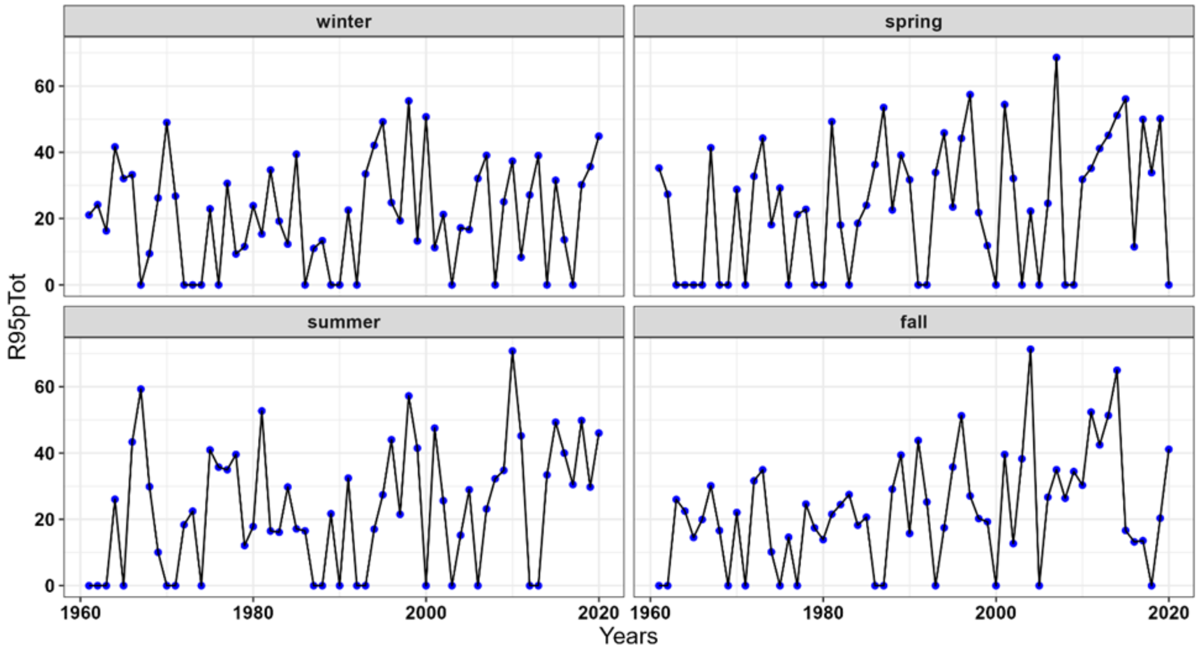


Figure 9. Seasonal values of R95pTot during the period 1961-2020 in Novi Sad

Table 9. Minimum, mean and maximum values of R95pTot during two periods: 1961-1990 and 1991-2020

R95pTot	1961 - 1990			1991 - 2020		
season	**min**	**mean**	**max**	**min**	**mean**	**max**
Winter	0	17.4	49.0	0	24.7	55.5
Spring	0	19.8	53.5	0	28.2	68.6
Summer	0	18.7	59.3	0	28.1	70.8
Fall	0	16.5	39.4	0	29.0	71.3

Precipitation fraction due to extremely wet days (R99pTot)

Precipitation fraction due to extremely wet days (R99pTot) is shown in Fig. 10. Although it appears that the percentage of R99pTot is higher in winter in the first period (Fig. 10), Table 10 shows that the mean value of R99pTot is higher in the second period (7.9) than in the first period (5.5). This was a consequence of the high R99pTot values from 1991 to 2000 (Fig. 10). It can be seen that the percentage of precipitation attributable to extremely wet days was greater in spring, summer and fall in the second period (Fig. 10). The mean and maximum values of R99pTot increased in the second period, with the highest increase occurring in the fall (Table 10). For example, the mean value of R99pTot increased from 0.9 in the period 1961-1990 to 11.7 in the period 1991-2020, while the maximum value of R99pTot doubled (from 27.5 to 54.0).

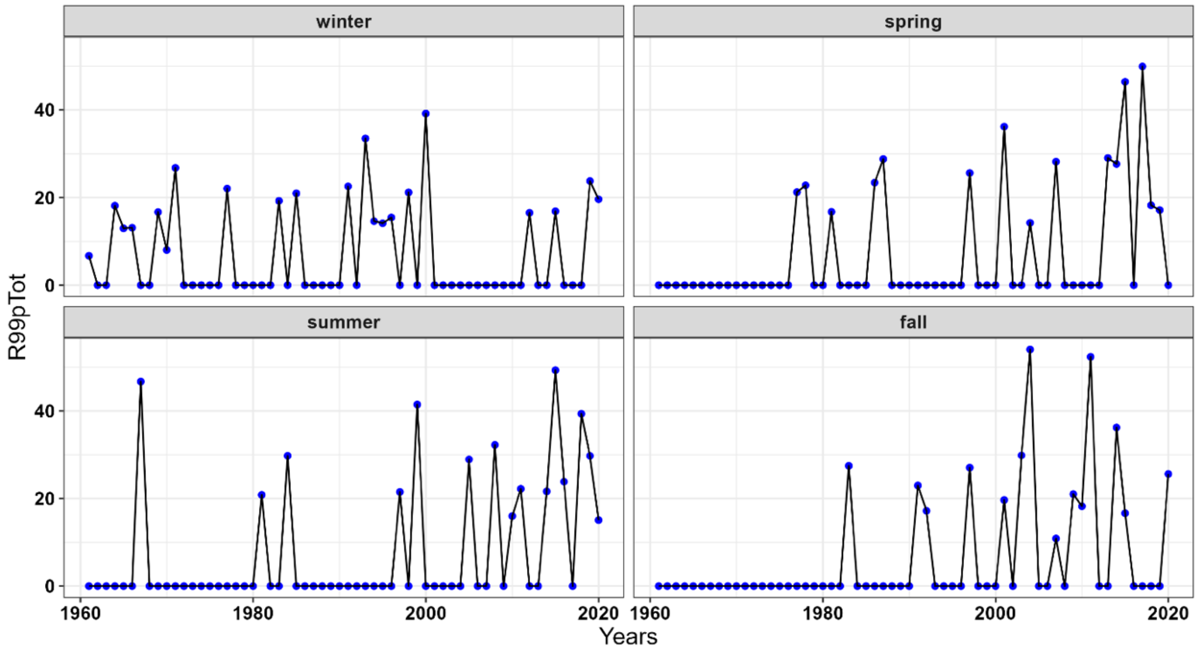


Figure 10. Seasonal values of R99pTot during the period 1961-2020 in Novi Sad

Table 10. Minimum, mean and maximum values of R99pTot during two periods: 1961-1990 and 1991-2020

R99pTot	1961 - 1990			1991 - 2020		
season	**min**	**mean**	**max**	**min**	**mean**	**max**
Winter	0	5.5	26.8	0	7.9	39.2
Spring	0	3.8	28.8	0	9.8	49.9
Summer	0	3.2	46.7	0	11.4	49.3
Fall	0	0.9	27.5	0	11.7	54.0

Trend analysis of seasonal EXPEs

The trend of EXPEs was calculated for all seasons and results obtained using the MMK test were presented in Table 11 for winter, Table 12 for spring, Table 13 for summer and Table 14 for fall. Table 11 shows that a positive trend prevailed in winter. A negative trend was identified for R20mm and R99pTot in winter (Table 11). There was no significant trend for seven indices. A significant positive trend was only observed for R95pTot and Rx3days.
A significant positive trend was observed for all indices in spring (Table 12) and fall (Table 14). A significant positive trend was observed for R95pTot, R99pTot, Rx1day, Rx3day and Rx5day in summer (Table 13).

Table 11. The Modified Mann- Kendall test results (Z), p-value (pv), Sen's slope (sen) and trend (trend_mdf) for time series of all indices in winter

Index	Z	pv	sen	trend_mdf
R10mm	0.8640	0.3875	0	No Trend
R20mm	-0.1215	0.9032	0	No Trend
R95p	1.1622	0.2451	0	No Trend
R95pTot	2.1818	0.0291	0.0620	Positive Trend
R99p	1.4151	0.1570	0	No Trend
R99pTot	-0.9462	0.3440	0	No Trend
Rx1day	1.6098	0.1074	0.0333	No Trend
Rx3day	3.0160	0.0025	0.0833	Positive Trend
Rx5day	1.0458	0.2956	0.0290	No Trend

Table 12. The Modified Mann- Kendall test results (Z), p-value (pv), Sen's slope (sen) and trend (trend_mdf) for time series of all indices in spring

Index	Z	pv	sen	trend_mdf
R10mm	3.0790	0.0020	0.0384	Positive Trend
R20mm	4.5340	5.78E-06	0.0198	Positive Trend
R95p	4.0652	4.79E-05	0.0454	Positive Trend
R95pTot	7.3259	2.37E-13	0.2818	Positive Trend
R99p	2.3198	0.0203	0	Positive Trend
R99pTot	2.1617	0.0306	0	Positive Trend
Rx1day	6.5839	4.58E-11	0.2426	Positive Trend
Rx3day	4.7071	2.51E-06	0.3010	Positive Trend
Rx5day	4.1435	3.42E-05	0.3064	Positive Trend

Table 13. The Modified Mann- Kendall test results (Z), p-value (pv), Sen's slope (sen) and trend (trend_mdf) for time series of all indices in summer

Index	Z	pv	sen	trend_mdf
R10mm	1.2335	0.2173	0	No Trend
R20mm	1.3318	0.1829	0	No Trend
R95p	1.4315	0.1522	0	No Trend
R95pTot	5.7474	9.067E-09	0.3224	Positive Trend
R99p	1.8878	0.0590	0	No Trend
R99pTot	2.4546	0.0141	0	Positive Trend
Rx1day	4.8792	1.06E-06	0.35	Positive Trend
Rx3day	5.0675	4.03E-07	0.3827	Positive Trend
Rx5day	4.4239	9.69E-06	0.3802	Positive Trend

Table 14. The Modified Mann- Kendall test results (Z), p-value (pv), Sen's slope (sen) and trend (trend_mdf) for time series of all indices in fall

Index	Z	pv	sen	trend_mdf
R10mm	5.5435	2.96E-08	0.0434	Positive Trend
R20mm	4.1394	3.48E-05	0.0200	Positive Trend
R95p	7.1969	6.15E-13	0.0510	Positive Trend
R95pTot	8.2301	1.86E-16	0.3374	Positive Trend
R99p	2.2884	0.0221	0	Positive Trend
R99pTot	2.2294	0.0257	0	Positive Trend
Rx1day	5.7814	7.40E-09	0.2000	Positive Trend
Rx3day	6.3697	1.89E-10	0.3211	Positive Trend
Rx5day	6.3408	2.28E-10	0.3546	Positive Trend

Annual analysis

The annual analysis shows an increase in all indices (Fig. 11 and Table 15). The number of days with more than 10 mm (R10mm) and 20 mm (R20mm) was highest in 2014, 53 and 20, respectively (Fig. 11). The highest daily precipitation (Rx1day) was 121.9 mm in 2015 (Fig. 11). In addition, the highest 3-day (Rx3day) and 5-day precipitation amounts (Rx5day) were measured in 2015, 149.4 and 162.3 mm, respectively. The secondary maximum was observed in 2018, 116.2 mm for Rx1day, 130.1 mm for Rx3day and 133.2 mm for Rx5day. The highest number of very wet days (R95p) and extremely wet days (R99p) was 51 and 16 respectively in 2014 (Fig. 11). As can be seen from Fig. 11, significantly more R95Tot and R99Tot occurred after 1995. In Novi Sad, a significant positive trend was observed for all indices (Table 15).

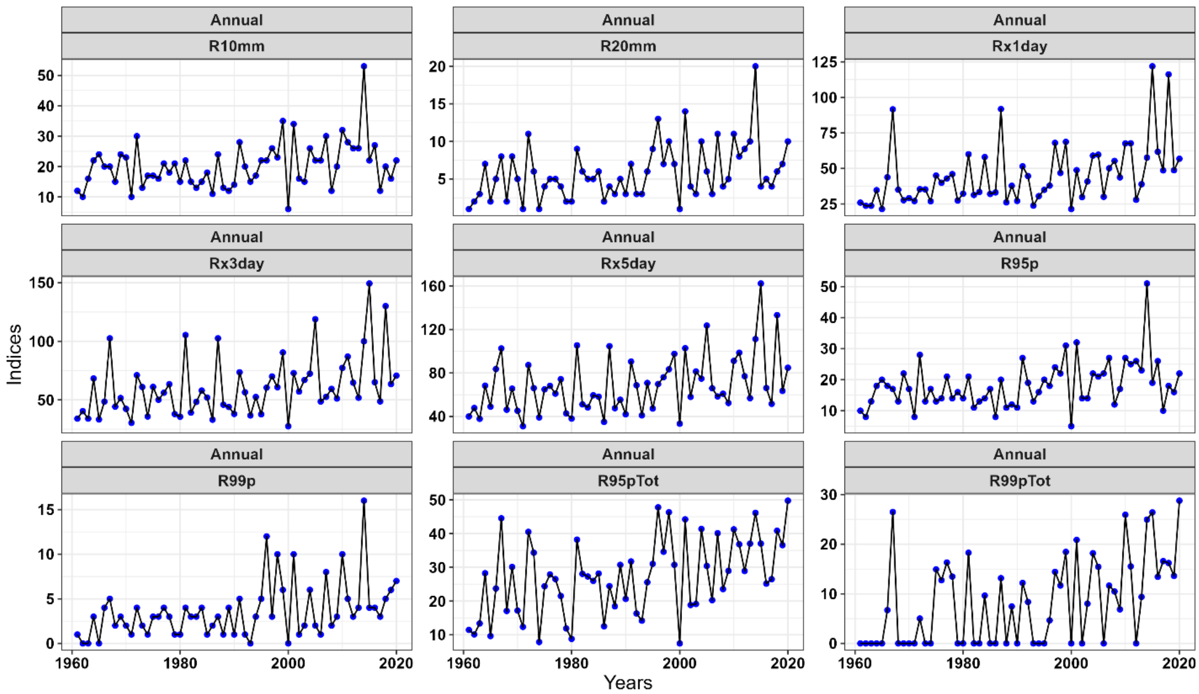


Figure 11. Annual values of climate indices listed in Table 1 during the period 1961-2020 in Novi Sad

Table 15. The Modified Mann- Kendall test results (Z), p-value (pv), Sen's slope (sen) and trend (trend_mdf) for the annual time series of all indices during the period 1961-2020

Index	Z	pv	Sen	trend_mdf
R10mm	5.1871	2.14E-07	0.1234	Positive Trend
R20mm	8.6622	4.63E-18	0.0714	Positive Trend
R95p	6.9202	4.51E-12	0.1428	Positive Trend
R95pTot	11.370	5.9E-30	0.3261	Positive Trend
R99p	6.5170	7.17E-11	0.0555	Positive Trend
R99pTot	7.7639	8.23E-15	0.2186	Positive Trend
Rx1day	9.1368	6.43E-20	0.4586	Positive Trend
Rx3day	8.0207	1.05E-15	0.4898	Positive Trend
Rx5day	7.3926	1.44E-13	0.5131	Positive Trend

The statistical analysis was then carried out for two reference periods 1961-1990 and 1991-2020. The results are shown in Table 16. The comparison of the values in the two periods under consideration shows that the mean and maximum values of all indices increased in the second period (Table 16). The minimum values of all indices fell or remained the same in the period 1991-2020, with the exception of Rx5day.

Table 16. Minimum, mean and maximum values of climate indices during two periods: 1961-1990 and 1991-2020

	1961 - 1990			1991 - 2020		
Index	min	mean	max	min	mean	max
R10mm	10.0	17.4	30.0	6.0	23.2	53.0
R20mm	1.0	4.4	11.0	1.0	7.3	20.0
Rx1day	21.4	38.2	91.8	21.4	51.9	121.9
Rx3day	30.4	52.3	105.4	27.5	69.2	149.4
Rx5day	31.0	58.9	105.4	33.3	78.4	162.3
R95p	8.0	15.1	28.0	5.0	21.3	51.0
R99p	0	2.3	5.0	0	4.9	16.0
R95pTot	7.9	22.5	44.5	7.4	31.9	49.8
R99pTot	0	4.8	26.5	0	11.7	28.8

An influence of the large-scale circulation on extreme precipitation events (EXPEs)

In order to investigate the influence of the large-scale atmospheric circulation on the EXPEs in Novi Sad, the Pearson correlation coefficient was calculated, the results of which are shown in Table 17. A positive correlation was found between the climate indices and the EA pattern and a negative correlation with the EAWR pattern (Table 17). A significant positive correlation was found between R95p, R95pTot, R99p, R99pTot, Rx1day, Rx3day, Rx5day and EA, and a strong negative correlation between R20mm, R95p, R95pTot, R99p, R99pTot and EAWR. The influence of NAO on EXPEs was weak during the whole 1961-2020 period in Novi Sad.

Table 17. Correlation coefficient between the climate indices listed in Table 1 and teleconnection patterns: the North Atlantic Oscillation (NAO), the East Atlantic pattern (EA) and the East Atlantic Western Russia (EAWR) pattern

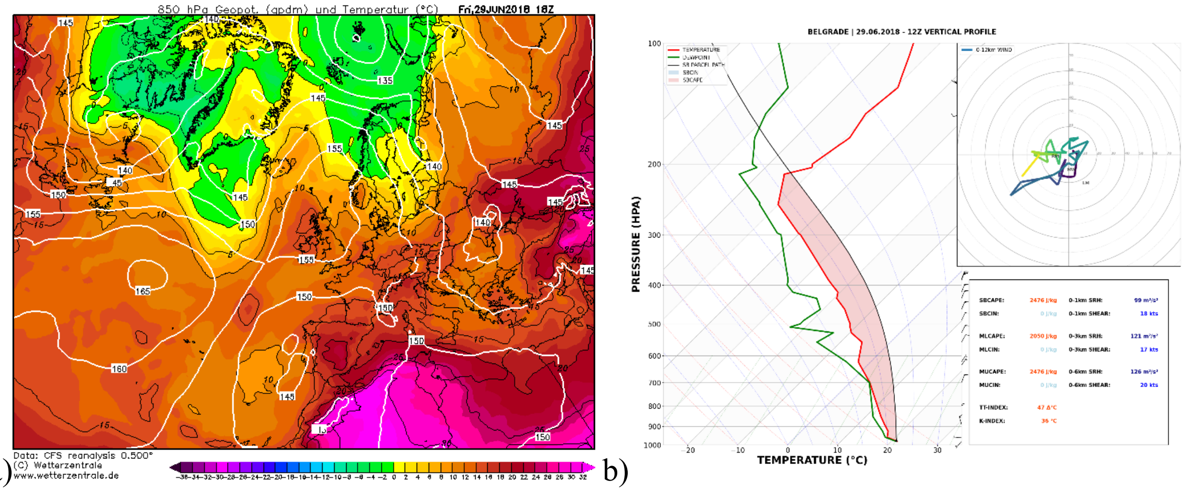
Index	NAO	EA	EAWR
R10mm	-0.0808	0.2259	-0.2249
R20mm	-0.0392	0.2239	**-0.3245**
R95p	-0.0762	**0.2617**	**-0.2591**
R95pTot	0.0854	**0.2997**	**-0.3133**
R99p	-0.0544	**0.3087**	**-0.3857**
R99pTot	0.0774	**0.3311**	**-0.3984**
Rx1day	0.2173	**0.3280**	-0.2527
Rx3day	0.1668	**0.3165**	-0.2519
Rx5day	0.1495	**0.3085**	-0.2223

Coefficients being significant at the 5% level are bolded

Discussion

The EXPEs were examined on an annual and seasonal basis and for two reference periods (1961-1990 and 1991-2020). We investigated the following indices: R10mm, R20mm, Rx1day, Rx3day, Rx5day, R95p, R99p, R95pTot and R99pTot. The Modified Mann–Kendall (MMK) test was used to assess trends in the EXPEs series over two time periods considered. Compared to the classical Mann–Kendall (MK) test, the MMK offers the advantage of reducing bias from serial dependence in time series while retaining the robustness and non-parametric, distribution-free properties of the original MK test. In our study, positive trends were observed for all annual and seasonal values of the indices with the exception of R20mm and R99pTot in winter. A significant positive trend was obtained for all annual values, spring and fall seasons. Leščešen et al. (2023) applied the peak-over-threshold method for the same 1961-2020 period as we did, with the threshold set at the 90th percentile, and found a significant increase in the frequency of extreme precipitation. For example, a total of 11 extreme years occurred from 2000 onwards, compared to six events before 2000 (Leščešen et al., 2023). Savić et al. (2020) analyzed the possible influence of urban factors on EXPEs in Novi Sad by establishing precipitation-climate indices and proposing to relate them to the pluvial flood hazard according to historical events.

In 2014, extreme rainfall of more than 200 mm in 72 hours was recorded and catastrophic flooding occurred in Bosnia, Croatia and Serbia (Tošić et al., 2014). An area of around 20,000 km^2 was flooded, which was unprecedented (Tošić et al., 2017). The maximum annual values of RR10mm, RR20mm, Rx1day, Rx3day, Rx5day, R95p and R99p were also measured in Novi Sad in 2014 (Fig. 11). A significant increase in Rx1day, Rx3day and Rx5day was observed in all seasons (with the exception of Rx1day and Rx5day in winter) and on an annual basis. High mean values of Rx1day (39.1 mm), Rx3day (53.6 mm) and Rx5day (60.6 mm) were measured in summer (Figs. 4, 5 and 6), compared to other seasons. The mean values of Rx1day, Rx3day and Rx5day were 25.9 mm, 37.9 mm and 43.8 mm in fall, 26.8 mm, 38.6 mm and 42.9 mm in spring, while lower values of 18.2 mm, 26.7 mm and 31.3 mm were recorded in winter, respectively. The high summer value of Rx1day (116.6 mm) was measured in Novi Sad in 2018, caused by convective rainfall, which led to flooding in the city due to a high proportion of impermeable surfaces and limited drainage systems (Savić et al., 2020). The meteorological situation that led to this flooding episode is shown in Fig. 12a. Figure 12a shows that Serbia is located in a region with increased geopotential and is under the influence of a very warm air mass. A low-pressure area is located much further north. A vertical profile of the temperature over Belgrade (sounding station closest to Novi Sad) on June 29, 2018 using data from the University of Wyoming (https://weather.uwyo.edu/upperair/sounding.html) and applying the Metpy Python library (May et al., 2022) is shown in Fig. 12b. The negative Lifted Index (-3.20), the high CAPE value (1093.93 J/kg) and the favorable K (36) and Totals Totals (TT) indices (47.6) indicate an environment that favors strong convective development and leads to severe thunderstorms. A high temperature and a very unstable atmosphere favored strong convection and caused the heaviest precipitation in northern Serbia. Precipitation was locally very intense (Fig. 13), which is confirmed by the fact that the value of RX1day for Novi Sad on June 29, 2018 was 116.6 mm, which is three times the average summer RX1day (39.1 mm). Our results are in line with the findings of other researchers (Marchi et al., 2010; Guerreiro et al., 2017), who found that flash floods in continental climates occur more frequently in the spring or summer months.



a) b)

Figure 12. (a) 850 hPa Geopotential Height obtained from reanalysis (wetterzentrale.de) and (b) vertical profile for Belgrade for 29/06/2018 at 18 UTC

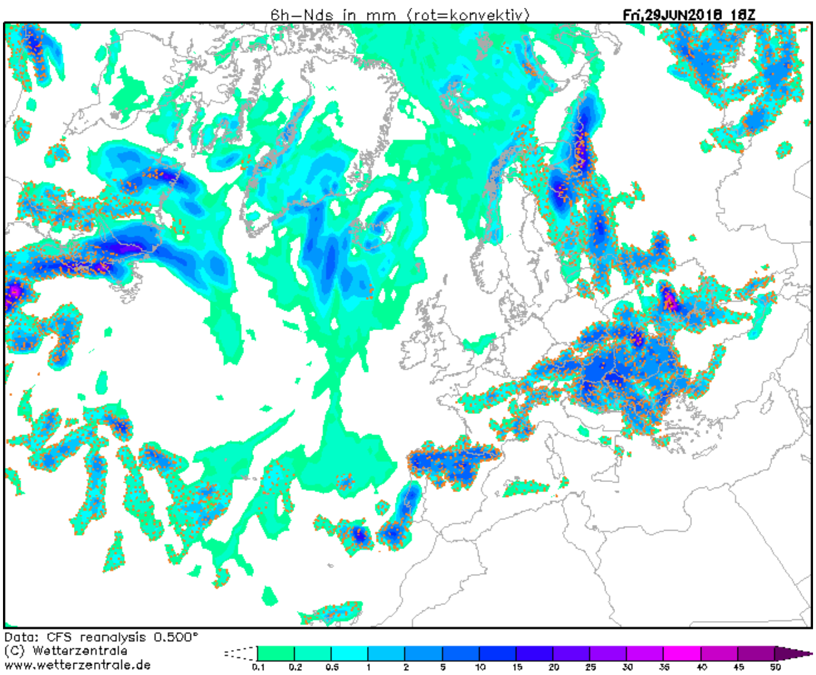


Figure 13. Precipitation data for 29/06/2018 at 18 UTC obtained from reanalysis (wetterzentrale.de)

This research and its results can contribute to the local community by providing reliable indicators of the increasing frequency and intensity of extreme precipitation, which is crucial for planning adaptation measures and reducing flood risk. The data obtained can be used to establish early warning systems, to adapt infrastructure - including the construction of more resilient buildings and the improvement of drainage systems (Yang et al., 2020; Mehvar et al. 2021) - and to support responsible spatial planning, thereby strengthening the resilience of the local population. In addition, the data can be useful for planning and investing in flood defence infrastructure (protective walls, dikes) as well as green infrastructure, a comprehensive approach that incorporates natural elements such as wetlands, green roofs and permeable pavements into urban planning (Dharmarathne et al., 2024). In this way, research contributes directly to the protection of public health (Sustainable Development Goals - SDG 3), the development of sustainable and safe cities and settlements (SDG 11) and the implementation of climate action through adaptation to change (SDG 13).

It should be emphasized that a strong positive correlation was found between the annual values of the climate indices R95p, R95Tot, R99p, R99pTot, Rx1day, Rx3day and Rx5day and EA, and a negative correlation between RR20mm, R95p, R95Tot, R99p, R99pTot and EAWR pattern. A correlation between the indices and the NAO was weak (Table 17). This result was not expected, as previous literature found a strong influence of the NAO on precipitation in Serbia (Tošić, 2004) and Vojvodina (Tošić et al., 2014). In their studies (Tošić, 2004; Tošić et al., 2014), the annual precipitation totals were analyzed, while in our case the number of days with daily precipitation greater than or equal to 10 mm, 20 mm and the 95th and 99th percentiles, as well as the fraction of precipitation due to very wet and extremely wet days were investigated. A negative correlation between EXPEs and the EAWR was expected, as Tošić and Putniković (2021) indicated that there was a precipitation surplus in Serbia when the EAWR was in a negative phase. A strong positive influence of the EA pattern on the temperature-climate indices in Serbia, including Novi Sad, was also found by Tošić et al. (2023). According to Ruml et al. (2017), the positive phase of the EA is associated with the transport of warm air over Serbia. In a warming climate, more frequent extreme precipitation events are expected.

Conclusions

Extreme precipitation events (EXPEs) were analyzed on the basis of daily precipitation recorded in Novi Sad, Serbia. The absolute and percentile climate indices were analyzed on an annual and seasonal basis for the entire observation period 1961-2020 and for two reference periods (1961-1990 and 1991-2020). All indices increased in the period 1991-2020 compared to the period 1961-1990, with the exception of R20mm and R99pTot in winter. A significant increase in Rx1day, Rx3day and Rx5day was observed in all seasons (except Rx1day and Rx5day in winter) and on an annual basis. This indicates an increasing frequency of high intensity precipitation events, especially in spring and summer. Of all the indices considered, Rx1day was found to be most strongly related to flood risk. The high value of Rx1day (116.6 mm) was measured in Novi Sad in the summer of 2018, when flooding occurred in Novi Sad. The intense rainfall was of convective origin and led to flooding in the city due to local terrain characteristics and limited drainage systems. The possible influence of large-scale circulation patterns on EXPEs was investigated. A significant positive correlation was found between R95p, R95pTot, R99p, R99pTot, Rx1day, Rx3day and Rx5day and EA, and a strong negative correlation between R20mm, R95p, R95Tot, R99p, and R99pTot and EAWR. Since a significant positive trend was observed for all annual

EXPEs, it is to be expected that extreme daily precipitation will occur more frequently in the future. It is therefore necessary to prepare for heavy precipitation, which can lead to flooding.

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Urban Stormwater Management with Rain Gardens – A Case Study of Kecskemét, Hungary

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Abstract
This research explores the potential benefits of rain gardens, a form of nature-based solutions (NbS) for urban stormwater management in Kecskemét, Hungary. An experimental rain garden was established using plants with varying drought tolerances to capture rainwater from a single-family house roof. This garden was monitored for a year to assess its rainwater retention capacity and observe plant development and survival. Concurrently, we identified areas within Kecskemét prone to flash floods from heavy rainfall, demarcating promising locations for rain garden conversion. Our primary goal was to identify applicable plant species and quantify how much rainfall could be retained in rain gardens. Our results show that drought-tolerant plants (e.g. *Festuca amethystina, Festuca pallens glauca*) perform better in the dry conditions typical of Kecskemét. Based on our calculation, the possible rainwater retention is about 1,500 m³, with 60 planned rain gardens. These findings suggest that the widespread urban application of rain gardens, as a nature-based solution, can significantly contribute to mitigating flash floods and enhancing urban resilience to extreme weather events.

Keywords: rain garden; stormwater; water retention; extreme precipitation; Hungary

Introduction
Urban areas worldwide face mounting pressure on water resources as climate change intensifies (Löscher et al., 2017). The spread of impermeable surfaces due to urbanization disrupts the natural water cycle, curtailing infiltration and evaporation crucial for maintaining stable urban microclimates (Osheen & Singh, 2019). This disruption triggers several issues: excessive runoff reduces water available for evapotranspiration, leading to soil desiccation and stressed green spaces (Osheen & Singh, 2019), while heavy rainfall events increasingly cause flash floods on sealed surfaces, washing pollutants into water systems. These

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challenges underscore the need for sustainable solutions that emulate natural water management processes.

The "sponge city" concept (Zevenbergen et al., 2018) is one of the possible solutions, which integrates green spaces, rain gardens, storage facilities, and green roofs into urban landscapes (Jiang et al., 2018; Nguyen et al., 2019). Blue-green infrastructure builds on sponge city principles, tackling water retention and drainage by merging ecological and engineering approaches (Wang et al., 2022; Zareba et al., 2022; Zhang et al., 2022). This involves surface elements for permanent or temporary water retention and subsurface storage to manage stormwater sustainably (Rosenberger et al., 2021; Tokarczyk et al., 2017). Across Europe, escalating rainfall intensity strains traditional drainage systems, often designed for outdated historical rainfall patterns (Ashley et al., 2005; De Toffol et al., 2009). In response, European urban planning increasingly incorporates the principles of nature-based solutions (NbS) through the implementation of blue-green infrastructure to manage excess rainfall, mitigate floods, and improve urban livability (Liu et al., 2019). The NbS concept refers to strategies that use natural features and processes to address societal challenges – such as climate change, food and water security, and natural disasters – while preserving biodiversity and promoting sustainable development (O'Hogain & McCarton, 2018). Specific examples of such green infrastructure, like rain gardens and constructed wetlands, are critical NbS applications that support broader climate adaptation efforts in Hungary by reducing runoff volume into sewers (Ge et al., 2023; Liao et al., 2017; Siwiec et al., 2018).

A rain garden is a landscaped depression designed to collect, treat, soak, filter, and retain rainwater from roofs, driveways, or streets, using modified soil and specific plants (Boguniewicz-Zablocka & Capodaglio, 2020; Kelly et al., 2020). As urbanization continues, innovative and cost-effective solutions are vital to combat rising flash flood risks, which occur when intense, short-duration rainfall overwhelms the ground's infiltration capacity, especially in sealed urban environments. While traditional sewer systems are costly to build and maintain, rain gardens offer a more economical alternative, though their effectiveness depends on local soil and watershed characteristics (Boguniewicz-Zablocka & Capodaglio, 2020; Ishimatsu et al., 2017; O'Donnell et al., 2017).

Climate change impacts are particularly pronounced in Hungary's "Homokhátság" region (Danube-Tisza Interfluve), including the city of Kecskemét. Rising temperatures and extreme weather have led to decades of desiccation. In Kecskemét, a city without natural surface watercourses, these extremes manifest as flash floods during heavy rains, especially in low-lying areas with extensive paving or impermeable saline soils (Luo et al., 2018; Papagiannaki et al., 2017). Kecskemét's 2021 Climate Strategy outlines rainwater management principles focused on water retention: 1) reducing runoff coefficients by increasing green areas, 2) property-level regulations for rainwater retention, and 3) promoting rainwater utilization (infiltration, evaporation) (Kecskemét Megyei Jogú Város, 2021).

Rain gardens align perfectly with these goals. The increasing frequency of flash floods (e.g., 2011, 2015, 2018, 2020, 2021, 2024) disrupts traffic, causes public dissatisfaction, and inflicts financial damage, particularly on city-center retail. Rapid water drainage post-flood further worsens drought conditions. Thus, in the water-scarce Homokhátság, retaining water and reducing water use are important goals.

Research on rain gardens in semi-arid regions like Homokhátság is limited, though examples from the US and Mediterranean exist (Herrera et al., 2017; Jiang et al., 2015). This study's novelty lies in its specific Central Eastern European context, demonstrating that even plants not typically listed for rain gardens can be viable. It highlights the potential of incorporating local native vegetation, regardless of initial drought or moisture tolerance assessments. In drier climates, selecting species with lower water needs yet resilient to occasional flooding is particularly beneficial.

Therefore, this research aims to answer:

1. What insights can an experimental rain garden offer regarding suitable plant species and water retention capacity?
2. Which green areas in a flood-exposed sample area of Kecskemét are suitable for rain garden development?
3. How much water could potentially be retained by rain gardens in this study area?

Data and Methods

Study Area

Kecskemét (population 108,120 in 2022) is situated in the Homokhátság region (Figure 1), an area highly vulnerable to climate change and exposed to aridification. The city's economy, once dominated by agriculture, is increasingly industrial, highlighted by a large automotive plant established in the early 2010s, now occupying 450 hectares.

The selected study area, encompassing approximately 2 hectares, is situated in the city center of Kecskemét. A key topographical feature of this site is its lower elevation relative to the adjacent urban landscape. Consequently, it functions as a natural catchment, accumulating surface runoff from the surrounding areas. This characteristic renders the area particularly susceptible to inundation by flash floods during heavy rainfall events, making it a pertinent location for studying rainwater retention strategies. The land cover is predominantly characterized by impervious surfaces, such as urban pavement, typical of a residential zone.

Figure 1. The location of Kecskemét in Hungary and the study area

The average temperature in Kecskemét rose by 3.5°C between 1991 and 2019 (KSH, 2024). The urban heat island effect is pronounced in densely built-up areas and the paved inner city, where summer night temperatures often remain above 20°C. July-August average temperatures reach 30°C, with highs up to 37°C. Climate models project extreme aridity for the region by century's end, with frequent severe droughts (Kecskemét Megyei Jogú Város, 2021).

However, climate change here doesn't necessarily mean less rainfall overall. Average annual precipitation has varied significantly in the last 15 years, from 359 mm to 881 mm (Figure 2). Rainfall distribution is uneven; while it might seem drier, especially during summer heatwaves, a substantial portion of precipitation often falls in large, intense events. In Kecskemét's multi-story residential and densely built-up areas, stormwater flows into a closed drainage network. The city's separated sewer system prevents rainwater from overwhelming the smaller-capacity sewage network during extreme events. Kecskemét has 20 water catchments: 1-16 (2,121 hectares total) drain into the Csukásér main channel, while 17-20 flow into an upper stormwater reservoir (Kecskemét Megyei Jogú Város, 2020). With typical annual rainfall of 500-550 mm, approximately 12 million m³ of rainwater and wastewater are drained from the city annually.

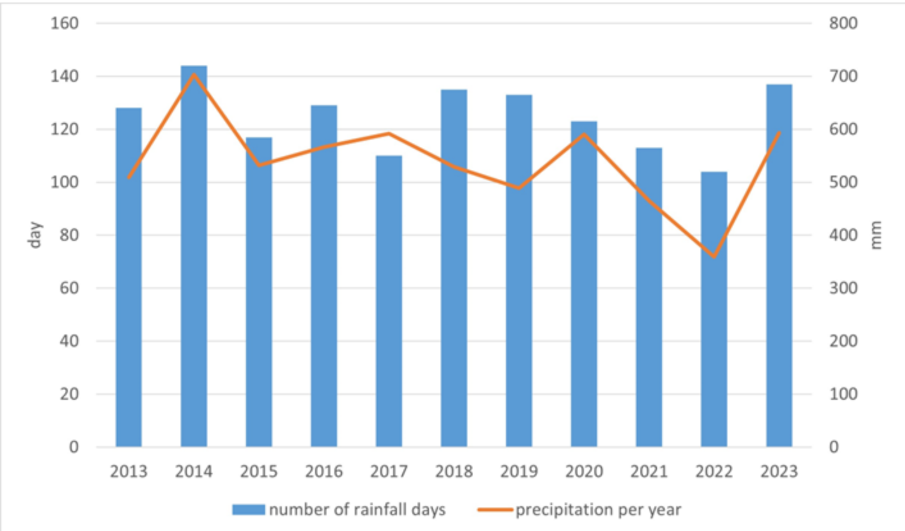

Figure 2. The average annual amount of precipitation and the number of rainfall days by year in Kecskemét (2013-2023)
Source: Central Statistical Office (KSH)

The flood issues from extreme weather are concentrated in our selected study area (Figure 1). This area acts as a catchment for surrounding higher-lying streets, frequently flooding (approx. 10 mm/h) during intense downpours (Figure 3). HungaroMet (met.hu) data indicate such events are increasingly common: over the last 50 years, daily summer precipitation amounts have risen by over 2 mm, while the number of rainy days has fallen (HungaroMet, 2024).

Figure 3. Flash floods in the study area (Vágó street) in 2020 June (left) and August (right)
Source: Levente Szekeres

Methodology

The study employs a two-pronged approach to answer the research questions. First, a small experimental rain garden was created to test plant viability. Second, we identified a nearly 140,000 m² downtown Kecskemét area exposed to flooding to assess its potential for rain garden implementation. Figure 4 outlines the research phases.

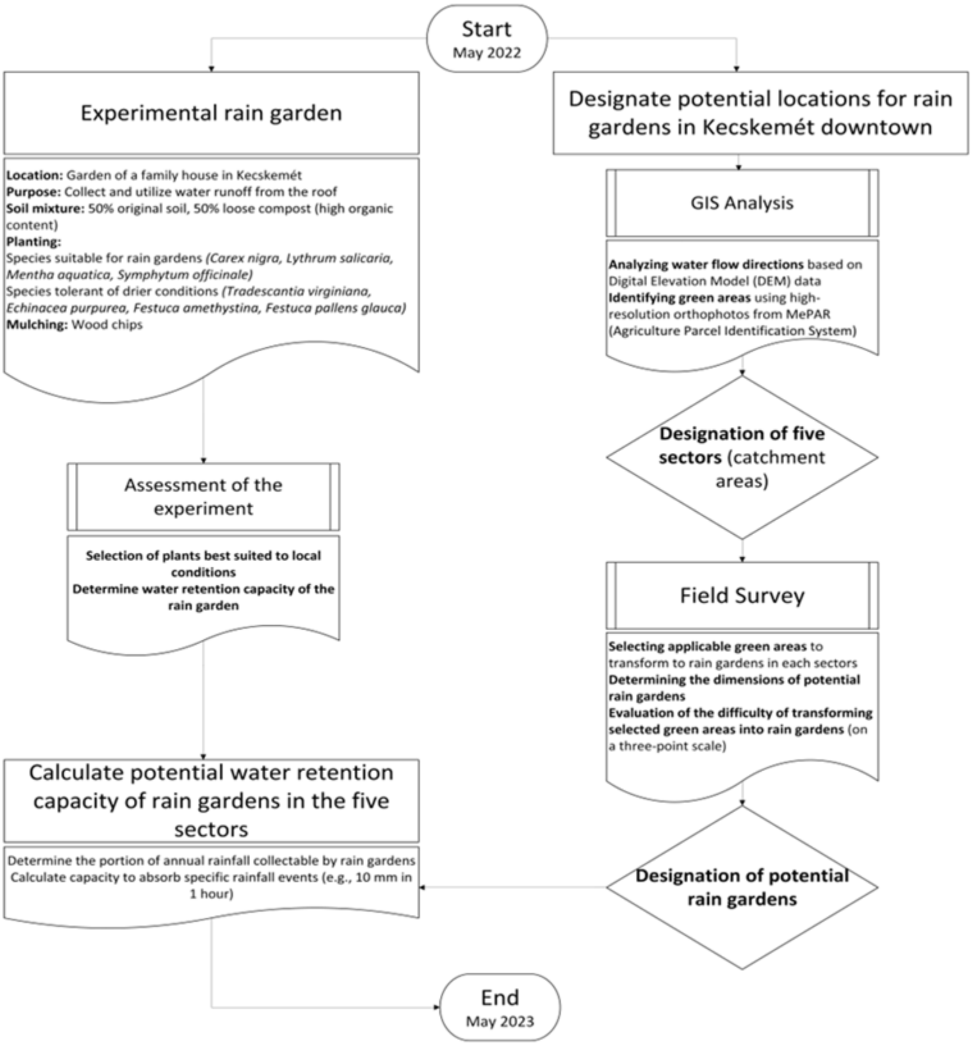

Figure 4. Flow diagram showing the connection between different research phases

Creation of a Rain Garden and Determination of Water Retention Capacity

An experimental rain garden was established in a family house garden in Kecskemét to collect roof runoff. The soil comprised a 50/50 mix of original soil and loose, high-organic-content compost from the local water utility, Bácsvíz Ltd. Selected plant species were planted, and bare soil was mulched with wood chips to conserve moisture, reduce transpiration, prevent erosion, and inhibit weeds. The experiment ran from May 2022 to May 2023. This one year was sufficient for testing the viability of the plants. However, monitoring of the vegetation in the experimental rain garden has continued since then.

Plant species selection was informed by Central and Eastern European literature and the Homokhátság's climate. We chose species commonly used in rain gardens (*Carex nigra, Lythrum salicaria, Mentha aquatica, Symphytum officinale*) and species tolerant of drier conditions (*Tradescantia virginiana, Echinacea purpurea, Festuca amethystina, Festuca pallens glauca*) (Kasprzyk et al., 2022; Bortolini & Zanin, 2018; Laukli et al., 2022; Vaculova & Stepankova, 2017). Plant viability was assessed by monitoring plant cover and health (leaf water availability, disease symptoms, growth) relative to their initial state.

Soil water retention capacity was the focus of soil testing, as permeability is key for rain gardens. The Hungarian Detailed Soil Physical and Hydrological Database (MARTHA) (Makó et al., 2010) indicates that Kecskemét's city center and the experimental site have sandy soils with high organic matter (Arenosols and Cambisols). Thus, detailed lab tests for soil type were deemed unnecessary, as practical compost ratios (40-50%) are standard. The soil properties of hypothetical urban rain gardens were assumed to match the experimental garden.

To evaluate water retention, one liter of an air-dry mixture of original sandy soil and compost was saturated with water. The amount percolating within 30 minutes was measured. Water began percolating after 29 seconds, with 0.3 liters dripping through by the end. Since 1.48 kg of the soil-compost mix is one liter, 1 liter of the mixture can hold 0.55 liters of water. The 3.04 m^2 experimental rain garden, filled with 1.51 m^3 of this soil-compost mix, had a water retention capacity of approximately 833 liters. This equates to 0.28 m^3 retention per square meter for a 60 cm deep rain garden. These results were extrapolated to estimate the potential capacity of urban rain gardens. Increasing rain garden depth proportionally enhances retention; our calculations represent a lower bound. The calculation was performed using the following formula (1):

$$V = \left(\frac{a+c}{2}\right) * m * l \qquad (1)$$

, where a is the width of the base of the trapezoidal depression formed for the rain garden = 50 cm,
c is the width of the top surface of the trapezoid = 80 cm,
m is the depth of the experimental rain garden = 60 cm,
l is the length of the rain garden = 380 cm.

The product of these measurements provides the volume of the depression, which we converted to cubic meters. The resulting volume was 1.48 m^3. Based on these measurements, the area of the rain garden was calculated to be 3.04 m^2.

Designation of Potential Locations for Rain Gardens and Determination of Water Retention Capacity

In the study area, we explored creating rain gardens in existing green spaces to collect runoff from paved surfaces and roofs. Green areas were identified manually in QGIS using MePAR (Agricultural Parcel Identification System) high-resolution orthophotos. The city's Digital Elevation Model (DEM) helped determine main flow directions, allowing us to select green surfaces lower than their surroundings to act as catchments. Public utility and drainage network locations were also considered using city GIS data. Potential rain garden sites were then manually designated, followed by field surveys for finalization. The study area was divided into five main sectors (catchment areas) (Figure 5), further subdivided into 12 sub-sectors for efficient analysis. Results are presented by the main sectors.

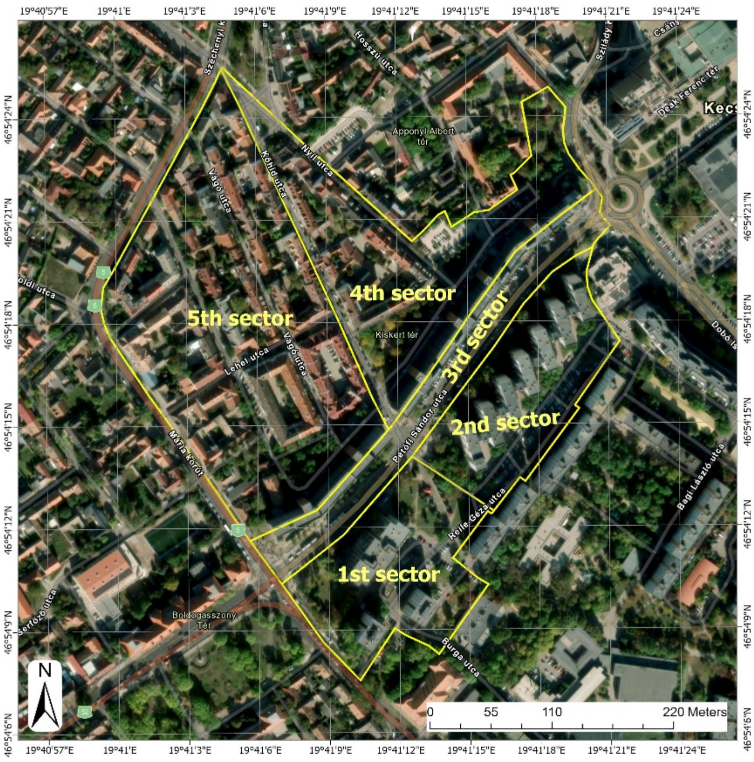

Figure 5. Five sector division of the study area

Within each sector, the estimated size of planned rain gardens was determined based on paved/unpaved surface ratios, allowing calculation of potential water retention. Comparing this with rainfall data (May 2022 – May 2023, Figure 6), we estimated the portion of annual rainfall retainable. We also calculated the capacity to absorb specific events (e.g., 10 mm rain in one hour).

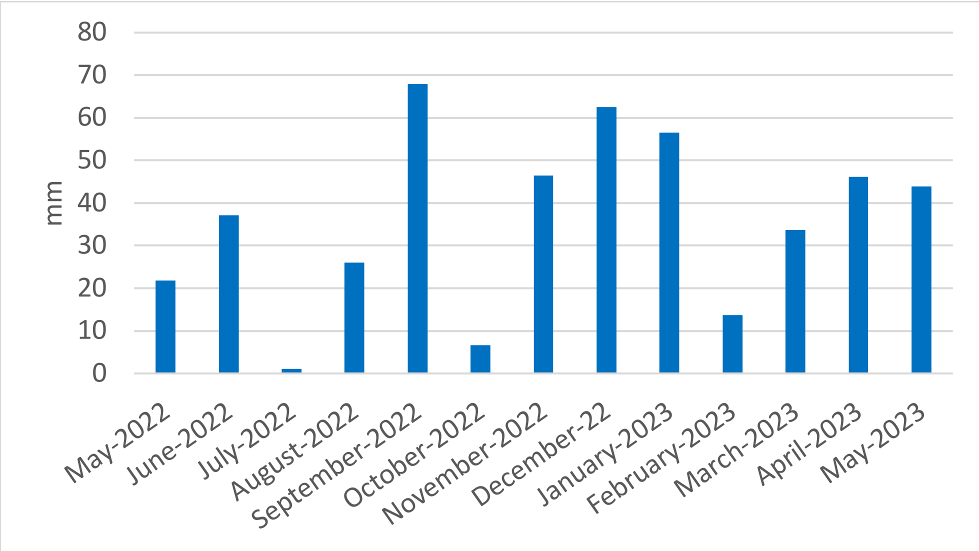

Figure 6. The average monthly rainfall in Kecskemét between May 2022 and May 2023.
Source: Central Statistical Office (https://www.ksh.hu/stadat_files/kor/hu/kor0056.html)

Extreme rainfall is increasingly frequent in Kecskemét. For instance, on August 4-5, 2020, nearly 70 mm fell in 12 hours (Netatmo weather station data), with several 30-minute periods seeing 15-20 mm (Figure 7). Such events highlight the inadequacy of existing drainage and the need for better stormwater management.

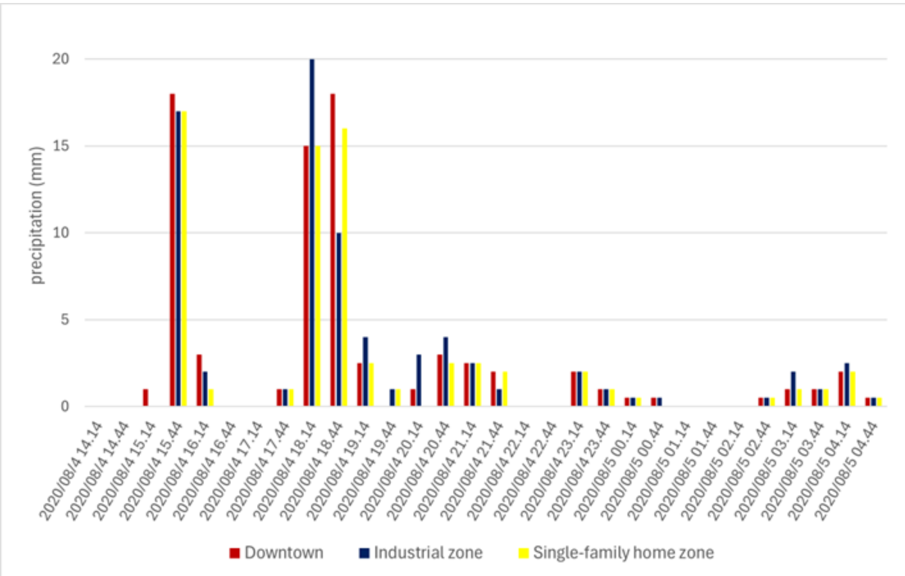

Figure 7. The amount of precipitation measured by Netatmo meteorological stations within 12 hours at various points in Kecskemét (August 4-5, 2020)

Results

Vegetation Viability in the Experimental Rain Garden

The experimental rain garden, with its two plant groups, functioned efficiently within six months. It successfully collected and retained roof runoff, even during heavy downpours and persistent rain. The permeability test showed the sandy soil-compost mix retained 0.55 liters/dm³. For our 3.04 m² garden, this meant a retention capacity of 0.83 m³ (approx. 0.28

m^3/m^2). This value was used to calculate the potential of urban rain gardens (assuming 60 cm depth, see Table 1). Retained water benefits not only garden plants but also nearby vegetation, promoting balanced water distribution.

Table 1. Comprehensive parameters of planned rain gardens by sector

Sector	**Area (ha)**	**Area of green surfaces (m^2)**	**Number of planned rain gardens**	**Total area of planned rain gardens (m^2)**	**Potential water retention capacity (m^3)**	**Floor area of buildings (m^2)**	**Number of buildings**	**Population (person)**
1	2.3	4,610	9	2,580	722	2,233	4	63
2	2.6	2,445	15	1,160	324	2,847	1	603
3	1.2	1,423	20	337.5	93	0	0	0
4	3.1	3,560	10	963	269	8,847	40	559
5	5.1	1,200	6	455	127	21,131	112	1,100
Total	**14.3**	**13,238**	**60**	**5,495.5**	**1,535**	**35,058**	**157**	**2,325**

Source: Compilation by own

The compost mixture provided adequate nutrients, evidenced by rapid plant recovery and growth. Soil life revived with the appearance of arthropods, and plants thrived (Figure 8). After an initial 200-liter watering at planting (absorbed by the soil mix), plants were watered only twice during the extremely dry summer (August 4 and 8, 2022). Otherwise, they relied on retained rainwater, developing primarily without additional irrigation.

Figure 8. The development of plants in the experimental rain garden (image "A" shows the plants after planting, while the image "B" shows them four months later)

Lythrum salicaria, initially questionable for survival, grew vigorously and bloomed, demonstrating its vitality (Figure 9).

Figure 9. *Lythrum salicaria* after planted (arrived almost without any leaves) (A) and its development two weeks (B) and two months later (C)

Plant species recommended by Vaculova and Stepankova (2017) and Laukli et al. (2022) showed less vigor in our setup. *Carex nigra* survival without irrigation is doubtful. *Mentha aquatica* appeared more durable. Drought-tolerant plants like *Festuca amethystine* proved more viable, all surviving without watering.

Water Retention Capacity of Planned Rain Gardens

Using GIS data for the study area, we calculated the total green surface area and determined the number and area of potential rain gardens. Assuming a 60 cm depth, the 60 planned rain gardens could retain over 1,500 m³ of rainwater. This capacity roughly equates to simultaneously collecting 10 mm of rainfall across the area. Importantly, runoff from higher-lying areas, especially to the northeast (Figure 10), and water collected by existing stormwater drainage, must also be considered.

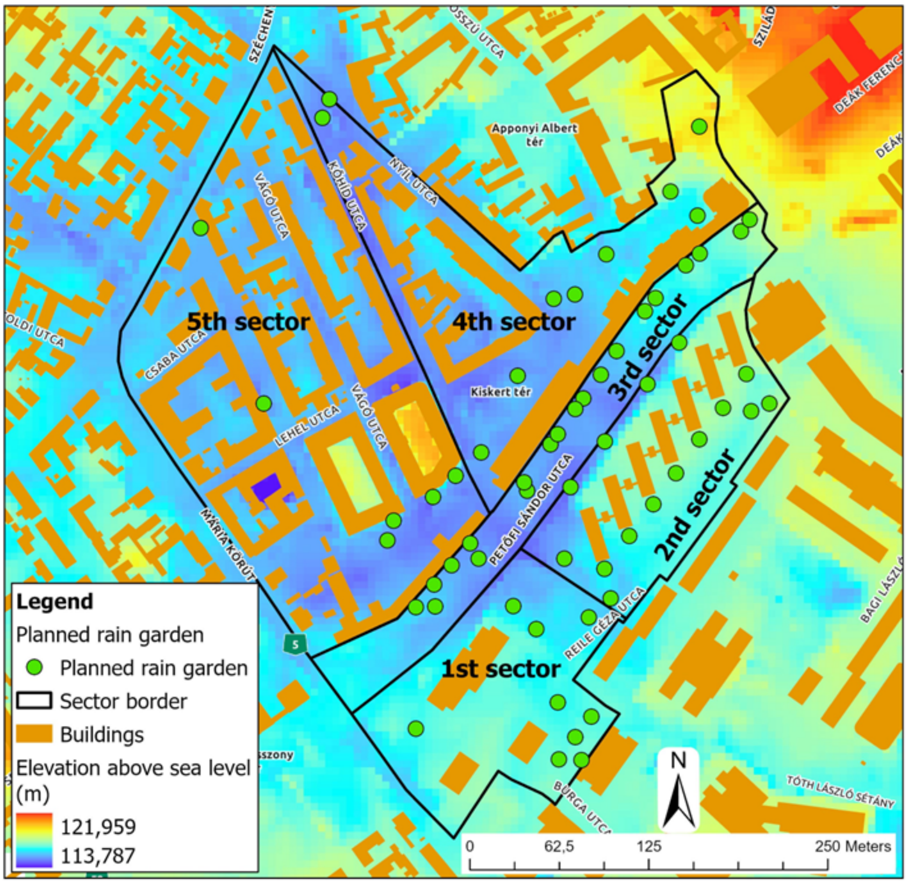

Figure 10. The location of the planned rain gardens on the DEM map (DEM data are provided by Lechner Knowledge Center)

Our measurements suggest a properly designed rain garden system in the study area could efficiently store a significant portion of rainwater from a major event (e.g., 10 mm/day). During more intense storms (e.g., 10 mm/hour), the system would reduce the load on the drainage network, allowing it to handle runoff more effectively. Table 1 details the characteristics and potential water retention per sector.

On the base of our measurements we classified the rain gardens by required implementation effort into three types (Figure 11):

- **Type 1 (40 sites):** Created on existing green surfaces with minor earthworks, no pavement disruption.
- **Type 2 (8 sites):** Smaller green areas, lower absorption capacity, but minimal land conversion.
- **Type 3 (12 sites):** Require major construction (pavement/sidewalk/curb modification), higher cost.

Of 60 potential sites, 40 (two-thirds) are Type 1, implementable without significant cost or construction (Table 2, Figure 11). Eight Type 2 sites, though offering limited space for rain gardens, also avoid major land conversion. Twelve Type 3 sites require significant modification and higher costs. Notably, 50% of Type 3 sites are in Sector 5, making it the most challenging for creating adequate retention capacity. This sector is also densely built-up with limited green space, meaning residential plots offer little contribution to water retention.

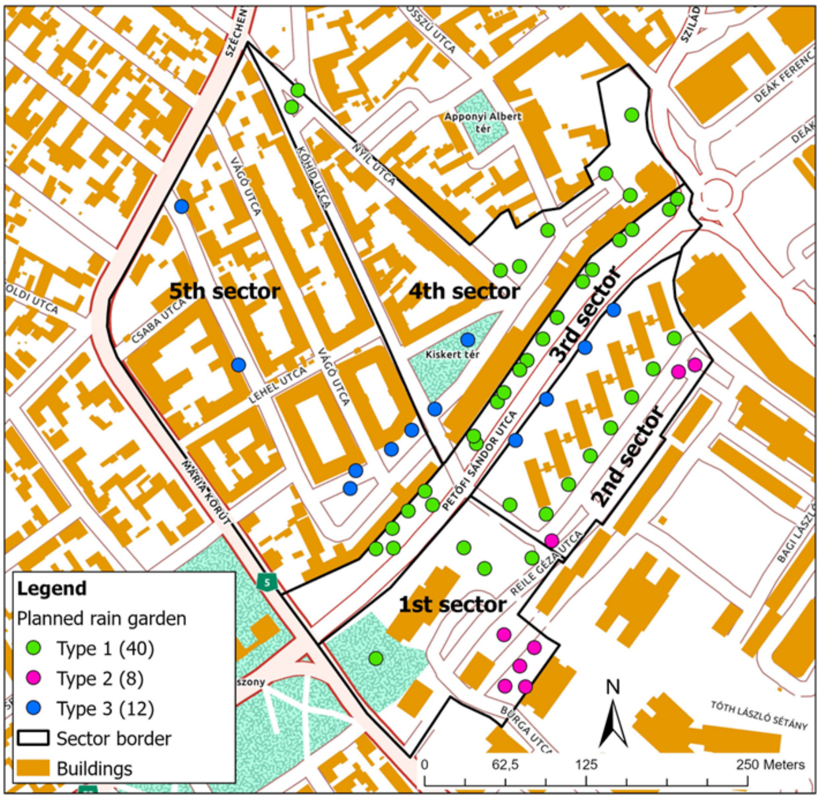

Figure 11. The location of different types of rain gardens in terms of the amount of construction required for implementation

Table 2. The suitability of different sectors for accommodating rain gardens

	Suitability for rain garden		
Sector	Type 1	Type 2	Type 3
1	4	5	
2	8	3	4
3	20		
4	8		2
5			6
Total	**40**	**8**	**12**

Source: Compilation by own

Discussion

The findings from the experimental rain garden and the Kecskemét study area indicate that this type of green infrastructure can significantly mitigate problems caused by flash floods. The potential installation of 60 rain gardens could retain approximately 1,500 m³ of water, sufficient to prevent flash floods even from a 100 mm rainfall event. This aligns with global research: a Kyoto study showed 60% stormwater retention (Zhang et al., 2019; Zhang et al., 2020), a Xi'an study found runoff coefficients reduced to near zero (Tang et al., 2016), and Montreal examples demonstrated up to 62% retention (Autixier et al., 2014) and Chinese models also predict high retention rate (53-100%) (Hou et al., 2020). Based on the latest calculations from Taiwan (Chen et al., 2024; Chen et al., 2025), if rain gardens were created on 10% of public spaces, they could collect approximately 48,000 to 710,000 m^3 of rainwater annually. In Taiwanese climate, this amount would be sufficient to meet the annual irrigation water needs of approximately 85 km² of vegetation-covered area and reduce annual runoff by 16%. Gdansk is one of the first Polish cities where rain gardens have been widely adopted. Here, rain gardens can handle 72% of the precipitation events studied (Burszta-Adamiak et al., 2023). Thus, according to the above findings, rain gardens are part of low-impact development (LID) systems that can effectively manage flash floods caused by heavy rainfall as part of urban stormwater management (Gulshad et al., 2024).

Studies identify diverse plant species suitable for rain gardens, with considerable heterogeneity even within Central Europe. For instance, a Nitra, Slovakia study prioritized ornamental plants preferring wetter conditions (e.g., *Liatris spicata*) (Bortolini & Zanin, 2018). In contrast, tests in colder Northern European climates included species like *Hemerocallis cv.* (Laukli et al., 2022), also common in Central European gardens. At the same time, plants that are known as indoor ornamental plants in Central Europe (e.g., *Chlorophytum comosum, Dracaena reflexa, Ruellia simplex, Sansevieria trifasciata*) are also viable in rain gardens under tropical conditions. These species showed good adaptability and a healthier morphological appearance in rain gardens compared to specimens living in traditional gardens (Chaves et al., 2025).

This highlights that optimal plant choices vary regionally, necessitating local studies (Doğmuşöz, 2024; Bruner et al., 2023). Consequently, different cities might need varied technological solutions and plant selections (Greksa et al., 2023; Suleiman et al., 2020), which also impacts construction and maintenance costs and economic viability (Kasprzyk, 2022).

Rain gardens have recently appeared in Kecskemét (2021/2022), proving effective. The Gerlice Street project (18 rain gardens) and the Shostakovich Street rain garden have successfully prevented previous flooding and waterlogging. These examples support our findings and indicate that converting green areas to rain gardens is an effective tool in urban development to solve complex environmental problems. A New York City study found traditional gray infrastructure 22% more expensive to build and maintain than blue-green alternatives for stormwater management (City of New York, 2011).

Wider application of our results may be limited by local, primarily climatic conditions. Thus, local studies are vital to determine soil water retention and ideal soil-compost ratios. Plant suitability requires preliminary viability testing, as poorly performing rain gardens can reduce public acceptance. Success is more likely with active local population involvement and awareness of benefits. Thus, while rain gardens offer significant potential, adaptation to local conditions and community needs is key for long-term success.

Finally, several limitations need consideration. The experimental garden was in a single-family home setting, not fully capturing urban complexities. While soil permeability was tested, other properties like organic matter content also affect long-term performance. The one-year duration may not capture long-term performance changes or challenges like soil compaction or clogging. The study focused on water retention and flood mitigation, with limited attention to other benefits like biodiversity enhancement or carbon sequestration.

Conclusions

This research explored rain gardens as elements of blue-green infrastructure, focusing on their role in urban climate adaptation and flash flood prevention. Our experimental rain garden in Kecskemét tested two plant groups: species typically found in wetter environments and drought-tolerant species (less tested in rain gardens previously). The results show that these drought-tolerant species plants are viable and applicable in sandy soil-based rain gardens. While plants adapted to wetter conditions were less well developed though still usable. Wetter-habitat plants would likely perform better in clay-rich soils.

To investigate the possible application benefits of rain gardens, we selected a flash-flood-sensitive area in Kecskemét. Using QGIS, we analyzed topography and utility networks, supplemented by field observations, to identify potential green areas for conversion to rain gardens. We found that constructing 60 rain gardens in the 140,000 m² study area could retain at least 1,500 m³ (1.5 million liters) of rainwater from average rainfall. During heavier precipitation, this would reduce the load on local stormwater drainage, decreasing flash flood likelihood. Water stored would gradually absorb into the urban soil, cooling the environment through vegetation evapotranspiration. The sustainable use of green-blue infrastructure worldwide can enhance rainwater management efficiency, making cities more resilient.

Municipalities should embrace nature-based solutions, e.g. rain gardens over conventional methods. Development plans should prioritize them, and the local dwellers needs clear information on the benefits of rain garden compared to traditional drainage. A follow-up study will examine Kecskemet's existing rain gardens' long-term hydrological performance, soil development and ecological succession under the changing climate conditions, which will further support urban stormwater management planning.

Acknowledgments

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Tourism and Regeneration in World Heritage Urban Areas: A Systematic Literature Review and Bibliometric Analysis

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Abstract
Tourism and regeneration are two interrelated factors that have a significant impact on World Heritage urban areas (WHUAs), places of outstanding cultural and historical values. However, the literature on the relationship between tourism and regeneration and their impact on these areas is still scarce and fragmented. This paper aims to provide a comprehensive and systematic review of the existing studies on tourism and regeneration in WHUAs and to identify the main research gaps and directions for future research. In this regard, we reviewed English published articles, conference proceedings, and book chapters indexed on Web of Science (WoS) and Scopus databases until 2023. We analyzed the publication trends, the most influential journals and publishers, the main research topics and methods, and the most applied approaches. The results revealed that in recent years, the Historic Urban Landscape, and culture-led urban regeneration approaches, as well as concepts such as authenticity and sustainability, have received the attention of researchers in this field. However, the literature also shows some limitations, such as a lack of theoretical and review studies, quantitative approaches, and a shortage of multiple-case studies. In addition, the factors for failure, consequences, and procedural solutions extracted as the key themes of the related projects. Based on these findings, this review provides insights valuable to researchers, urban planners, and policymakers involved in the conservation and development of these culturally valuable areas in ways that balance tourism growth with heritage preservation.

Keywords: tourism; regeneration; World Heritage; urban areas; systematic literature review; bibliometric analysis

Introduction
World Heritage Urban Areas (WHUAs) are invaluable sites that combine cultural, historical, and architectural significance. Due to their outstanding universal value, these locations attract millions of tourists each year, who support local economies through cultural tourism (Aslani et al., 2022; Bacsi & Tóth, 2019; Pedersen, 2002). In the light of this opportunity, many countries

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around the world have adopted regeneration policies aimed at revitalizing their WHUAs and enhancing their appeal (Mbhiza & Mearns, 2014; Xuili & Maliene, 2021).

While tourism promotes economic growth and helps fund conservation efforts, it also brings challenges that threaten the very heritage assets that attract visitors (Rössler, 2023). The influx of large numbers of tourists can cause complex social and spatial changes that affect the quality of life for locals, from overcrowding to environmental degradation as well as the loss of local culture (Enseñat-Soberanis & Blanco-Gregory, 2022; Semprebon, 2022). In particular, WHUAs face unique challenges because they serve both living spaces for residents and destinations for visitors, which increases concerns about authenticity, gentrification, and socio-economic imbalance as tourism grows (Jamieson & Engelhardt, 2018). Hence, the link between tourism and urban regeneration has become an important area of research (e.g. Lak et al., 2020; Li, 2020; Uysal & Özden, 2012), especially within WHUAs, where the conservation of historical and cultural assets must be compatible with tourism development. Despite the growing popularity of tourism-led urban regeneration initiatives, there is still a lack of systematic review of how tourism and urban regeneration interact in WHUAs. By integrating the fragmented knowledge in this context, this review aims to provide insights for developing theoretical and practical approaches to managing WHUAs, address important research gaps and limitations in previous studies, and summarize current knowledge on tourism and regeneration in WHUAs.

The specific research questions are:

- What are the key themes in studying tourism and regeneration in WHUAs?
- What methodologies and approaches were utilized to research tourism and regeneration in WHUAs?
- What are the gaps and future agenda for research on tourism and urban regeneration in WHUAs?

Also, bibliometric analysis questions are:

- How is the distribution of the selected records by year?
- How is the geographical distribution of the selected records' case studies?
- How is the keywords occurrence of the selected publications?
- What scientific journals have published papers on tourism and regeneration in WHUAs?
- Which publications contributed the most to publishing papers on this topic?
- What branches of science deal with this issue (i.e., urban studies, urban geography, history, cultural studies, etc.)?

Research Design

This study employs a mixed-methods approach combining a systematic literature review (following PRISMA guidelines), bibliometric analysis, and inductive content analysis to synthesize existing research on tourism and regeneration in World Heritage Urban Areas (WHUAs). These combined methods are well suited to synthesising a fragmented literature and highlighting research gaps by providing both qualitative depth and quantitative mapping of the field.

Systematic Literature Review

In the first step, a systematic review and meta-analysis were performed to achieve the stated aim. A systematic literature review is a method for identifying, interpreting, and evaluating all available research on a particular research issue, subject domain, or idea of interest (Suikkanen, 2020). It can be used to detect gaps in existing knowledge and propose future study directions (Chigbu et al., 2023).

In this study, as shown in Figure 1, the procedure follows PRISMA (Protocol for Reporting in Systematic Reviews and Meta-Analyses) 2020 statement inscribed by Page et al. (2021). The PRISMA protocol is a collection of recommendations designed to improve the quality of systematic reviews (Kelly et al., 2016). It includes a checklist and flow diagram to guarantee that systematic reviews are reported transparently and comprehensively (Sohrabi et al., 2021).

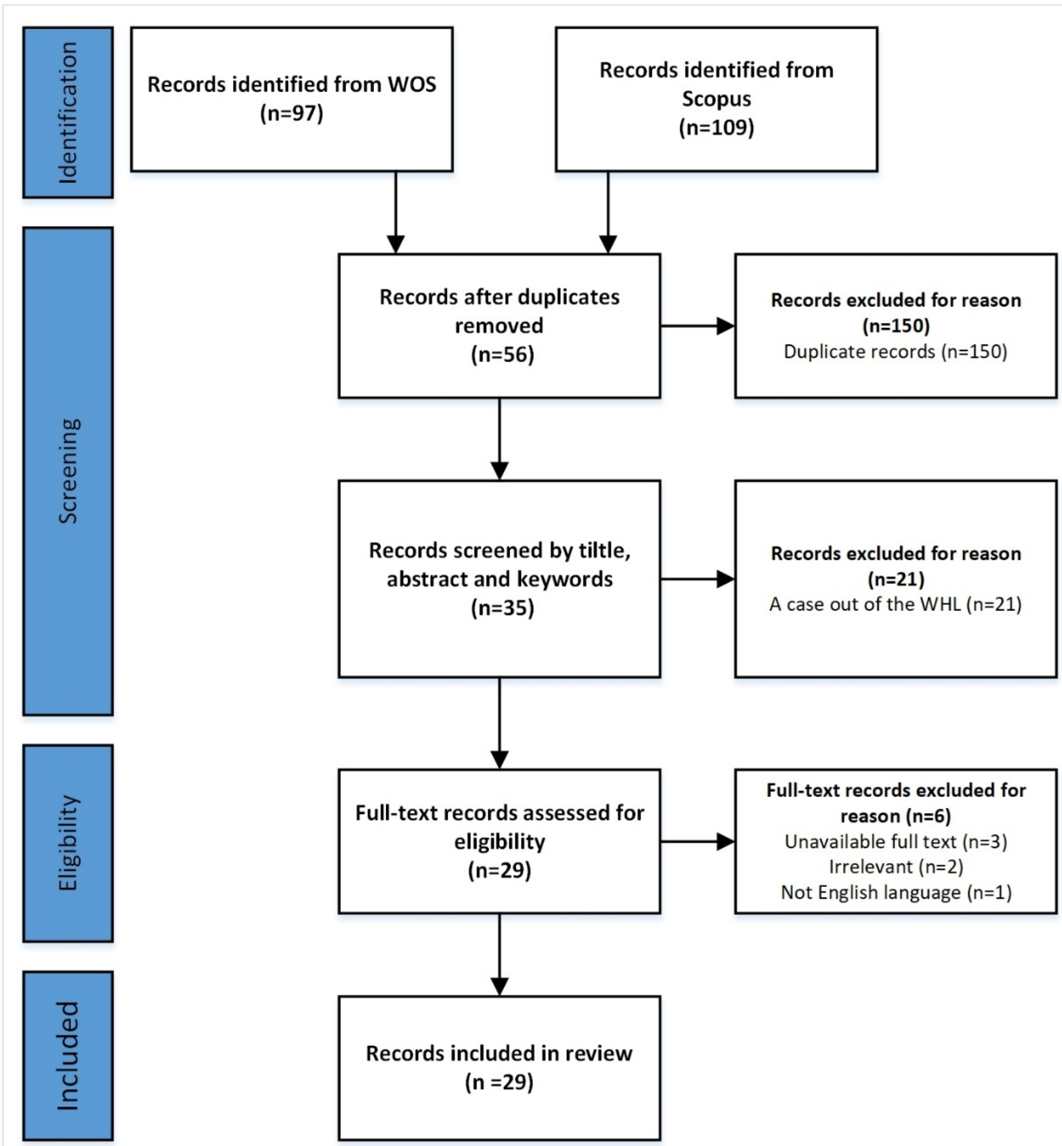

Figure 1. Flowchart PRISMA by levels

Records selection

Due to the robust query engines, excellent visualization tools, and the ability to automatically extract metadata from a wide range of academic publications, WoS and Scopus databases were selected for conducting the review (Putra et al., 2023; Valente et al., 2022).

A combination of keywords and Boolean operators—words such as AND, OR, and NOT, which are used to expand (OR) or narrow (AND, NOT) search results (Whitehead & Maude, 2013)—was used to construct the search query: (tourist OR tourism) AND (regeneration OR revitalization OR renewal) AND (urban OR city) AND (world heritage). The query is applied to the topic field, which includes the title, abstract, and keywords of the articles. The search process was conducted in March 2024, and 206 journal articles, conference proceedings, and book chapters were retrieved that match the search query. Then, the metadata of the records, such as the title, authors, journal, year, abstract, and keywords, was exported to a spreadsheet for further analysis. The researcher applied exclusion and inclusion criteria to the retrieved articles to filter out the irrelevant or duplicate ones during the selection process. The exclusion criteria are: the record is not written in English; the record is a duplicate of another one; the record whose full text was not available. The inclusion criteria are: the record addresses the concepts of tourism and regeneration in relation to WHUAs; and the record is a journal article, conference proceeding, or book chapter. The screening process results in 29 records that are included in the final sample.

Bibliometric Analysis

The second step involves conducting the bibliometric analysis of the selected literature. Bibliometric analysis summarizes scientific activity within a domain using statistical methods (Liu & Li, 2016). It comprises various factors, such as patents, types of publication, topic domain, available data-based research, annual publications, journals and publishers, etc. (Ramnath & Harikrishnan, 2021).

Year-wise distribution of studies

Distribution of records by year is shown in Figure 2. Accordingly, Topics related to tourism and regeneration in WHUAs first appeared in the literature in 2000. However, since 2018, the number of records has increased and this trend of continues until now. The majority of records (68.96% of the 29 entries) were between 2018 and 2023, indicating the topics' rising significance in the last 5 years.

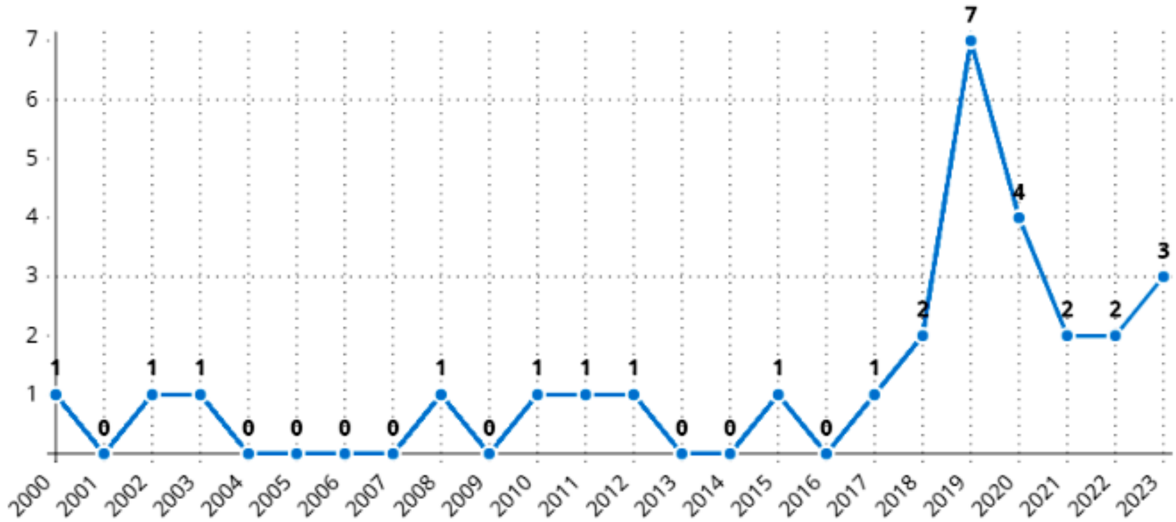

Figure 2. Distribution of records by year

Journals and disciplinary field

Out of the 32 records analyzed, 68.96% were journal articles, 17.24% were conference proceedings, and 13.80% were book chapters, respectively (Figure 3).

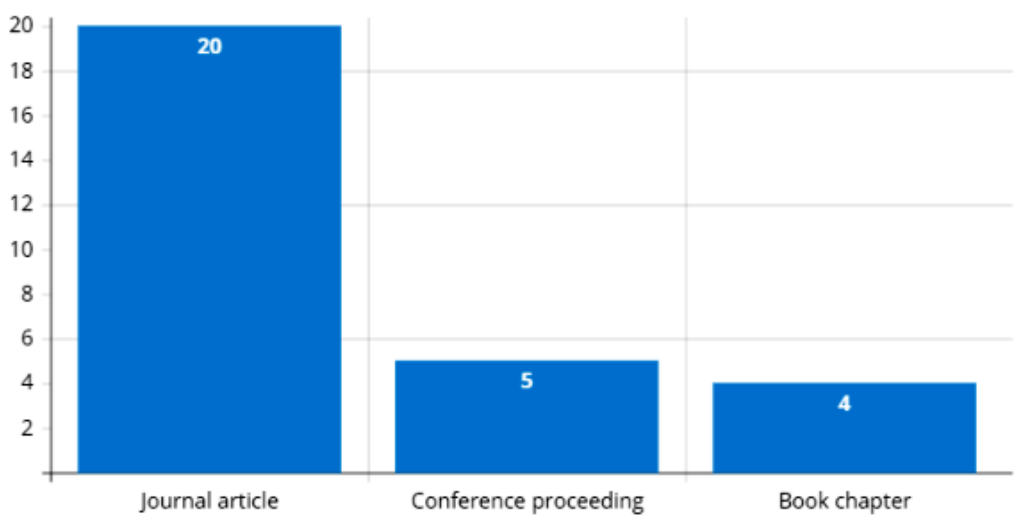

Figure 3. Final records based on the type

The articles were published in 16 different journals (Table 1), which cover a range of eight disciplinary fields and twenty-nine sub-disciplines (Table 2). Among the journals, Sustainability and International Journal of Heritage Studies have the highest volume of publications (3), with only one record found in the remaining journals. The diversity of the academic disciplines indicates the multidisciplinarity of the studied topic. It should also be noted that most journals cover multiple fields of study, which may also serve as justification for this diversity. Although the journal Sustainability can be considered an exception because it publishes articles in different disciplines. For example, energy and computer science are mentioned in Table 3, but they are not related to the studied topic. Also notable are the contributions of publications relating to "geography, planning and development" (22.22%), followed by "urban studies" (11.11%), and "tourism, leisure, and hospitality management" (9.26%). It is noteworthy that journals related to "architecture" and "conservation" were less involved in the subject under study. As a result, architecture and conservation journals do not welcome the combination of topics related to tourism and urban regeneration. Also, the journals published by Taylor & Francis publications had the largest share in accepting the articles.

Table 1. Number of articles per journal and publisher

Journal title	Publisher	Counts
Built Heritage	Springer Nature	1
Erdkunde	University of Bonn	1
Historic Environment: Policy and Practice	Taylor & Francis	1
Human Organization	Taylor & Francis	1
International Journal of Heritage Studies	Taylor & Francis	3
Sustainability	MDPI	3
Land	MDPI	1
URBAN DESIGN International	Taylor & Francis	1
Journal of Place Management and Development	Emerald Publishing	1
Journal of Tourism and Cultural Change	Taylor & Francis	1
On the waterfront	University of Barcelona	1
Open House International	Emerald Publishing	1
Planning Malaysia	Malaysian Institute of Planners	1
Tourism	Croatian Institute for Tourism	1
Tourism Geographies	Taylor & Francis	1
Urban Geography	Taylor & Francis	1

Table 2. Disciplinary fields and sub-disciplines covered by journals

Disciplinary field	Sub-discipline	Counts
Arts and Humanities	Archeology	1
	Arts and Humanities	1
	Conservation	3
	History	3
	Museology	1
	Visual Arts and Performing Arts	1
Business, Management and Accounting	Business and International Management	1
	Marketing	1
	Strategy and Management	1
	Tourism, Leisure and Hospitality Management	5
Computer Science	Computer Science	1
	Hardware and Architecture	1
Earth and Planetary Sciences	Earth and Planetary Sciences	1
Energy	Energy Engineering and Power Technology	1
	Renewable Energy, Sustainability and the Environment	1
Engineering	Architecture	1
Environmental Science	Ecology	2
	Environmental Science	1
	Global and Planetary Change	1

	Management, Monitoring, Policy and Law	1
	Nature and Landscape Conservation	2
Social Sciences	Anthropology	1
	Cultural Studies	2
	Geography, Planning and Development	12
	Transportation	1
	Social Sciences	1
	Urban Studies	6

Keyword analysis

A network analysis of keyword co-occurrences with their timelines is given in Figure 4. The network map was created using VOSviewer software. The node size shows the weight of the keywords, which is determined by the number of occurrences, while the lines depict the connection between the keywords. A total of 157 keywords were extracted from the 29 records. Out of these, 124 had a single occurrence, representing 79% frequency, while just 33 (21%) had two or more co-occurrences. Because of it, and to ensure a more realistic visualization of the network, all keywords with at least one occurrence were included. This lower prevalence of keywords with two or more co-occurrences might be justified to some extent by the small number of records in the analysis. "Tourism" had the majority of occurrences, with 8 occurrences and a total link strength of 78, while "urban renewal" had the highest link strength, with 7 occurrences and a total link strength of 81. Other keywords based on the occurrences are "tourism development," "heritage," "heritage tourism," "UNESCO," "World Heritage Site," "urban regeneration," and "Historic Urban Landscape" respectively. Since these keywords made up the search code, this result was fairly expected. The point worth mentioning is that, from 2018, "Historic Urban Landscape" appeared in 4 records with a link strength of 18. In addition, compared to renewal and revitalization, regeneration has grown in prominence during the last decade.

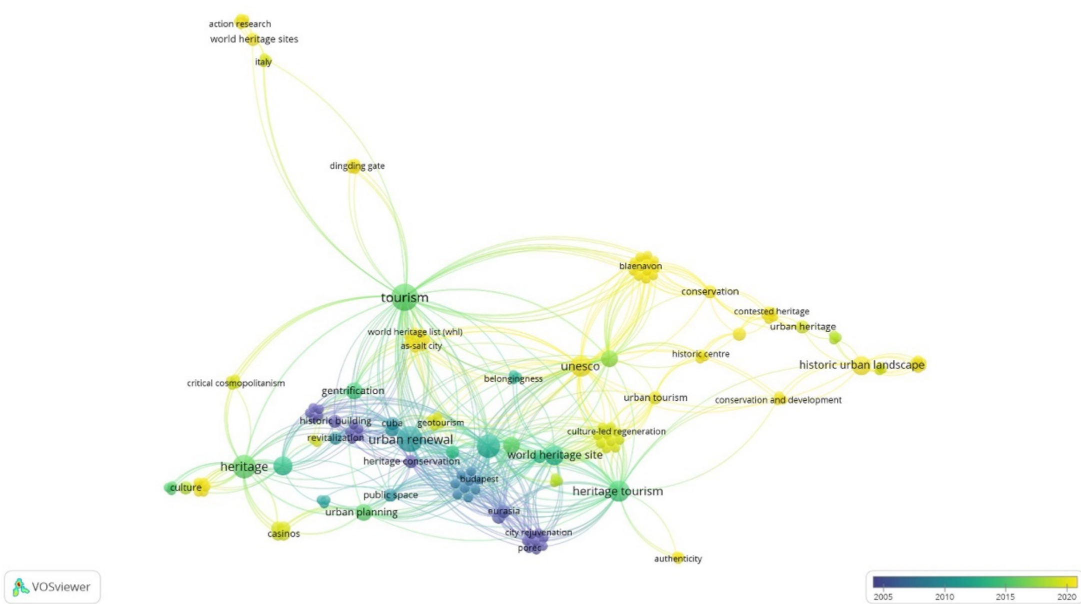

Figure 4. Keywords network by co-occurrence with the timelines

This analysis resulted in the identification of 15 clusters overall and 1039 links, with a total link strength value of 1101. The first one was formed around urban renewal, heritage conservation, revitalization, and transformation. The second cluster combined studies around heritage and culture. The third cluster emphasizes UNESCO and regeneration. The fourth cluster was related to urban heritage and conservation. The fifth cluster was more focused on urban regeneration, gentrification, public space, and historic building. Cluster 6 was centered on urban development, urban tourism, and tourist destination. Cluster 7 words were around the topic of Historic Urban Landscape. Following that, clusters 8, 9, 10, 11, and 12 evolved around themes such as cultural tourism development and tourist attraction; overtourism, participatory design, world heritage sites, and tourism development; cultural change, economic development, and tourism management; social exclusion; and tourism development. Eventually, clusters 13 to 15 were based on a single article that represented a wide range of subjects, including heritage tourism and authenticity as well as urban planning and flexibility.

Geographical context

According to Figure 5, Europe had the highest geographical concentration (44.44%), followed by Asia (38.89%), South America (13.89%), and North America (2.78%), while no relevant research is carried out in Africa and Australia. In the context of Europe, practically the most research was done in Italy (5), Portugal (4), and the UK (2). Within the Asian setting, the highest number of cases belonged to Malaysia (4) and China (3). Next, Cuba (2) had the greatest number of cases in the Caribbean region.

Two studies employed a multiple-case study approach from different countries located in Asia and Europe, as well as Asia and South America, while the rest focused on a single case study.

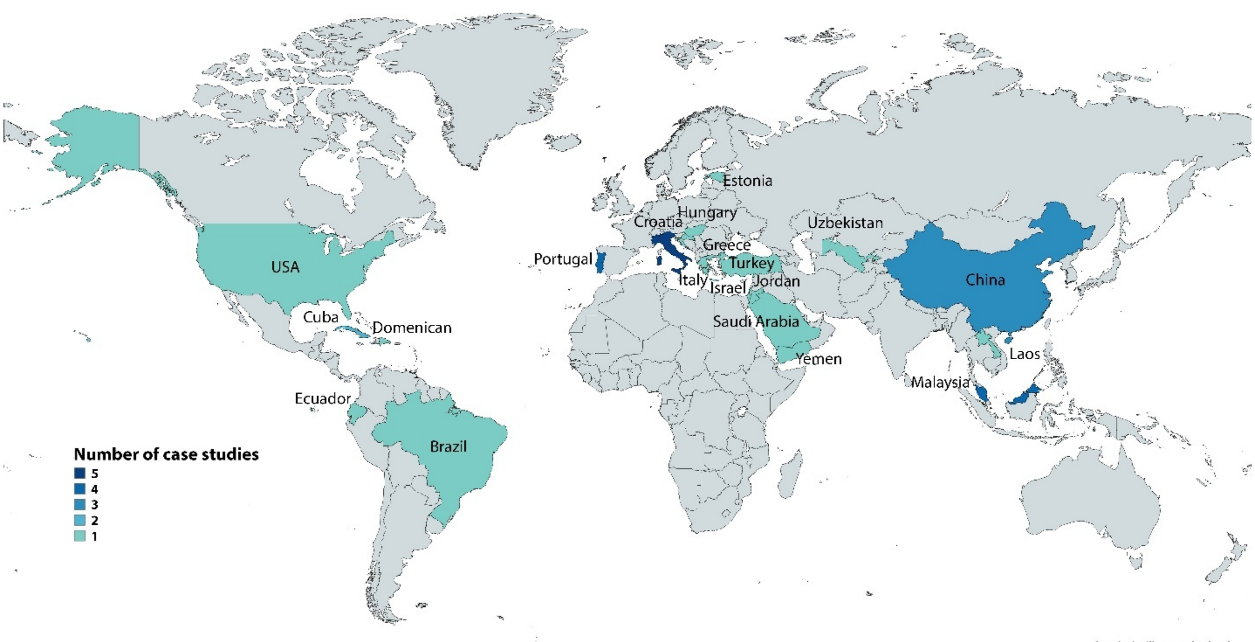

Figure 5. Geographic distribution of the records' case studies

Note: Kosovo and Metohija is an integral part of the Republic of Serbia, in accordance with United Nations Security Council Resolution 1244 (1999), under temporary UN administration

Content Analysis
The records were analyzed in terms of research methodology and research context using the inductive content analysis technique. The method is employed in the analysis of textual material in order to clarify hidden themes (Ghaderi et al., 2020). This process includes three steps: open coding, creating categories, and abstraction (Elo et al., 2014). The records were coded according to research inquiries and then grouped based on semantic and conceptual linkages, and each group was finally given a name (Ghaderi et al., 2022). Regarding the research context, the aim was to identify the primary domains where tourism and regeneration in WHUAs were adopted.

Research methods
The methods employed in the records are summarized in Table 3. All of the records were empirical studies. Out of all the records reviewed, 22 (75.9%) were qualitative, 6 (20.7%) were mixed, and 1 (3.4%) were quantitative. Secondary data analysis (such as institutional documents) 17 (34.69%), observation 14 (28.57%), interviews 9 (18.36%), informal conversations 3 (6.12%), comparative studies 2 (4.08%), questionnaires 2 (4.08%), Delphi method 1 (2.05%), and nominal group technique 1 (2.05%) were among the data retrieval techniques employed by qualitative approaches. Quantitative methods were particularly popular in topics concerning tourism-led regeneration and urban transformation (Čaušević & Tomljenović, 2003; Ciambrone, 2015; Colavitti & Usai, 2019; Höftberger, 2023; Michelson et al., 2020; Paz, 2011; Ratz et al., 2008; Ricca, 2018; Salim & Mohamed, 2018; Santos, 2019; Scarpaci, 2000; Soccali & Cinà, 2020; Ye, 2021; Zandonai, 2019), tourism development consequences and urban regeneration (Alberti, 2022; Bakri et al., 2023; Katahenggam, 2020; Zandonai, 2019), stockholders' attitude towards regeneration in tourism destinations (Del Baldo & Demartini, 2021; Peira et al., 2022; Schiller, 2019; Su et al., 2020), and urban regeneration and sustainable development of tourism destinations (Lombardi & Doganer, 2019). Among mixed methods approaches, the most frequently used techniques were composition of observation 5 (23.81%), secondary data analysis (such as official statistics) 5 (23.81%), statistics analysis 3 (14.28%), field mapping 2 (9.52%), interviews 2 (9.52%), questionnaires 2 (9.52%), informal conversations 1 (4.77%), and ethnography 1 (4.77%). These methods were especially implemented in studies pertaining to cultural heritage tourism and urban regeneration (El Faouri & Sibley, 2022; Gusman et al., 2019), tourism-led regeneration and urban transformation (González-Pérez, 2017; Nobre, 2002; Völkening et al., 2019), and tours and disseminating knowledge about urban regeneration projects (Santos, 2012). In the only quantitative research (Chua & Deguchi, 2010), questionnaires were applied to identify stockholders' attitudes towards regeneration in a tourism destination.

Table 3. Research methods

Author(s) and (year)	Research design	Method(s)	Target of data collection
Gusman et al. (2019)	Mixed	Observation; secondary data analysis; statistical analysis	n.a.
Ratz et al. (2008)	Qualitative	Secondary data analysis	n.a.

Nobre (2002)	Mixed	Observation; secondary data analysis; statistical analysis	n.a.
Bakri et al. (2023)	Qualitative	Interviews; observation	Cultural and heritage activists/practitioners; workers, residents; representatives of place of worship; traditional/non-traditional business traders; community leaders; heritage advocates, WH office staff; local planning authority representatives; local government staff; representatives of the tourism industry; community-based organisation representatives; and a Federal heritage department representative
Colavitti & Usai (2019)	Qualitative	Comparative analysis; secondary data analysis	n.a.
González-Pérez (2017)	Mixed	Field mapping; observation; secondary data analysis; statistics analysis	n.a.
Del Baldo & Demartini (2021)	Qualitative	Interviews; observation; questionnaires; secondary data analysis	Citizens and university students
El Faouri & Sibley (2022)	Mixed	Interviews; observation; statistics analysis	Local community
Michelson et al. (2020)	Qualitative	Secondary data analysis	n.a.
Alberti (2022)	Qualitative	Secondary data analysis	n.a.
Höftberger (2023)	Qualitative	Observation; secondary data analysis	n.a.
Scarpaci (2000)	Qualitative	Observation; interviews; secondary data analysis	Local residents and administrators
Čaušević & Tomljenović (2003)	Qualitative	Interviews; secondary data analysis	City mayor
Su et al. (2020)	Qualitative	Observation; secondary data analysis	Local residents; tourists; heritage experts; and heritage managers
Völkening et al. (2019)	Mixed	Field mapping; interviews; observation; secondary data analysis; statistical analysis	Residents
Katahenggam (2020)	Qualitative	Interviews; observation	Tourists
Santos (2019)	Qualitative	Informal conversations; interviews; participant observation	Tour attendees
Santos (2012)	Mixed	Ethnography; informal conversations; participant observation; questioniares; secondary data analysis	Tour guides
Salim & Mohamed (2018)	Qualitative	Observation; secondary data analysis	n.a.
Soccali and Cinà (2020)	Qualitative	Comparative analysis; secondary data analysis	n.a.
Ricca (2018)	Qualitative	Observation; secondary data analysis	n.a.

Zandonai (2019)	Qualitative	Informal conversations; interviews; observation; secondary data analysis	City residents; architects, an economist; former administrators
Ciambrone (2015)	Qualitative	Observation; secondary data analysis	n.a.
Paz (2011)	Qualitative	Observation; secondary data analysis	n.a.
Lombardi & Doganer (2019)	Qualitative	Secondary data analysis	n.a.
Ye (2021)	Qualitative	Informal conversation; observation; secondary data analysis	Residents; a shop staff; tourists; and students
Peira et al. (2022)	Qualitative	Delphi; interviews; nominal group technique	Trade associations; tourist associations; a tour operator; a tourist attraction manager
Schiller (2019)	Qualitative	Interviews; observation; questionnaires	Members of two non-profit associations; local residents and shop owners; and long-term street vendors
Chua & Deguchi (2010)	Quantitative	Questionnaires	Residents and business owners

Research topics

In total, factors for failure, consequences, and procedural solutions were the key themes that were extracted from a thorough, methodical full-text analysis of each record.

The factors for failure address the reasons that hinder the success of tourism-led urban regeneration projects. The consequences included advantages, referring to the benefits that tourism-led urban regeneration projects bring to an area, and disadvantages, focusing on the challenges arising from these projects. The procedural solutions deal with ways in which the challenges of the projects can be overcome and their benefits expanded.

T1: Factors for failure

Content analysis of the reviewed records indicated that these factors encompass projects with a state-run and top-down nature (Nobre, 2002; Scarpaci, 2000; Völkening et al., 2019), preference for tourism (El Faouri & Sibley, 2022; González-Pérez, 2017; Höftberger, 2023), beautification and restoration of historical buildings without adaptive reuse (El Faouri & Sibley, 2022; Ye, 2021), ignoring the site background and the stakeholders (Colavitti & Usai, 2019; Ye, 2021), and restriction of regeneration to a local plan (Ye, 2021).

T2: Advantages

Urban regeneration, in line with tourism, can offer physical, economic, and social benefits to urban areas (Rezaei et al., 2020). For instance, it contributes to the revitalization of areas that were previously devalued economically (Čaušević & Tomljenović, 2003; Gusman et al., 2019; Ratz et al., 2008; Salim & Mohamed, 2018), the conservation of heritage properties (Nobre, 2002; Zandonai, 2019), the enhancement of local quality of life (Čaušević & Tomljenović, 2003; Ratz et al., 2008), and the improvement of urban infrastructure (Höftberger, 2023; Scarpaci, 2000).

T3: Disadvantages

On the other hand, like any other phenomenon, tourism-led urban regeneration projects can lead to negative impacts on WHUAs, such as museification and commodification of heritage

(Colavitti & Usai, 2019; El Faouri & Sibley, 2022; Katahenggam, 2020; Scarpaci, 2000; Soccali & Cinà, 2020; Ye, 2021; Zandonai, 2019), overtourism (Alberti, 2022; Čaušević & Tomljenović, 2003; Colavitti & Usai, 2019; Gusman et al., 2019; Höftberger, 2023; Zandonai, 2019), gentrification and displacement of local inhabitants (Höftberger, 2023; Michelson et al., 2020; Santos, 2019; Scarpaci, 2000), threats to authenticity (Höftberger, 2023; Katahenggam, 2020; Su et al., 2020), creating unequal economic opportunities (Santos, 2019; Völkening et al., 2019), and dependence of the local economy on tourism (Michelson et al., 2020; Santos, 2019).

T4: Procedural solutions
The scholars suggested various solutions in response to mitigate the above disadvantages, like public participation (Alberti, 2022; Čaušević & Tomljenović, 2003; Chua & Deguchi, 2010; Ciambrone, 2015; Colavitti & Usai, 2019; Del Baldo & Demartini, 2021; El Faouri & Sibley, 2022; Gusman et al., 2019; Katahenggam, 2020; Lombardi & Doganer, 2019; Michelson et al., 2020; Peira et al., 2022; Ricca, 2018; Santos, 2012; Soccali & Cinà, 2020; Su et al., 2020), incorporating culture into regeneration strategies (Čaušević & Tomljenović, 2003; Colavitti & Usai, 2019; Del Baldo & Demartini, 2021; Gusman et al., 2019; Ratz et al., 2008; Ricca, 2018), considering sustainability (Alberti, 2022; Bakri et al., 2023; Colavitti & Usai, 2019; Gusman et al., 2019; Michelson et al., 2020), connecting the area to its surroundings (Čaušević & Tomljenović, 2003; Lombardi & Doganer, 2019; Michelson et al., 2020; Peira et al., 2022; Ye, 2021), implementing heritage management (Bakri et al., 2023; Colavitti & Usai, 2019; Del Baldo & Demartini, 2021; Ratz et al., 2008), fostering creative industries (Čaušević & Tomljenović, 2003; Del Baldo & Demartini, 2021; Paz, 2011; Ratz et al., 2008), raising local heritage awareness (Čaušević & Tomljenović, 2003; Santos, 2012, 2019; Soccali & Cinà, 2020), adaptive reuse aligning with the historic identity of the area (Chua & Deguchi, 2010; Ciambrone, 2015; Ye, 2021), balancing economic development with heritage preservation (Nobre, 2002; Salim & Mohamed, 2018; Su et al., 2020), flexibility in planning (Chua & Deguchi, 2010; Del Baldo & Demartini, 2021; Zandonai, 2019), considering mixed land uses in line with resident and tourist demands (Lombardi & Doganer, 2019; Salim & Mohamed, 2018), applying a dynamic assessment and monitoring mechanism (Colavitti & Usai, 2019; Gusman et al., 2019), funding conservation efforts with tax revenues from tourism activities (Zandonai, 2019), and including public spaces in the analysis of urban transformation processes (Paz, 2011).

Discussion and Conclusion

The systematic literature review and bibliometric analysis of tourism and regeneration in WHUA provides important insights into the current state of research in this area. The results of this study show that this issue has been emerging in the literature since the beginning of the 21st century and has received increased attention in recent years. In line with Nachmany and Hananel (2023), after reviewing the global experiences, it could be said that these projects act like a double-edged sword in such a way that they bring advantages and disadvantages together. Their advantages to WHUAs are economic redevelopment, the conservation of heritage properties, the enhancement of the local quality of life, and the improvement of urban infrastructure. Nevertheless, they also have several disadvantages, including museification and commodification of heritage, overtourism, gentrification and displacement of local inhabitants, threats to authenticity, creating unequal economic opportunities, and dependence of the local economy on tourism. The disadvantages mainly arise due to the state-run and top-down nature of these projects and other factors, such as a preference for tourism, the beautification and restoration of historical buildings without adaptive reuse, ignorance of the site background and stakeholders, and the restriction of regeneration to a local plan. The reviewed studies propose solutions that consist of public participation, incorporating culture into regeneration strategies, considering sustainability, connecting the area to its surroundings, implementing heritage management, fostering creative industries, raising local heritage awareness, adaptive reuse that aligns with the historic identity of the area, balancing economic development with heritage preservation, flexibility in planning, considering mixed land uses that align with resident and tourist demands, applying a dynamic assessment and monitoring mechanism, funding conservation efforts with tax revenues from tourism activities, and including public spaces in the analysis of urban transformation processes.

The intersection of urban regeneration and tourism studies in recent years has shown a growing trend towards the Historic Urban Landscape approach, culture-led development, authenticity, and sustainability (e.g., Aslani & Kapusta, 2025; García-Hernández et al., 2017; Light et al., 2020; Pezzi, 2017). This highlights a rising emphasis on preserving the cultural and historical values of WHUAs while promoting sustainable tourism and urban development (Prabowo et al., 2023).

As a comprehensive solution in response to the aforementioned concerns, the Historic Urban Landscape (HUL) approach was introduced by UNESCO in 2011 to better integrate heritage management with urban development (Veldpaus, 2015). By following HUL, cities can achieve their Sustainable Development Goals (SDGs) targets and become more sustainable, resilient, and inclusive in urban development (UNESCO, 2015). Additionally, through tourism, commercial use, and higher property values, a properly managed urban heritage can promote socio-economic development (UNESCO, 2013). The HUL approach can be achieved through the following key steps: “1. undertaking a full assessment of the city’s natural, cultural and human resources; 2. using participatory planning and stakeholder consultations to decide on conservation aims and actions; 3. assessing the vulnerability of urban heritage to socio-economic pressures and impacts of climate change; 4. integrating urban heritage values and their vulnerability status into a wider framework of city development; 5. prioritizing policies and actions for conservation and development, including good stewardship; 6. establishing the appropriate (public-private) partnerships and local management frameworks; 7. developing mechanisms for the coordination of the various activities between different actors” (UNESCO, 2013, p. 16). Future research might concentrate more on evaluating the connection between tourism and regeneration in WHUAs using the HUL approach.

The study also revealed limitations in the existing literature, such as a lack of theoretical and review studies, quantitative approaches, and a predominance of single-case studies. These limitations may have an impact on the scope and depth of the literature available for analysis. As a result, future research should aim to fill these gaps through more theoretical studies, quantitative methods, and a multiple-case study approach.

Furthermore, the findings of this study have implications for future research and practice in the field of tourism and regeneration in WHUAs. Key themes extracted, such as factors for failure, consequences, and procedural solutions, provide policymakers, urban planners, and heritage conservationists with practical insights. Understanding the challenges and opportunities associated with tourism and urban regeneration in WHUAs will assist in developing more effective and sustainable strategies for preserving cultural assets and encouraging responsible tourism. A study agenda was also proposed for future directions from a theoretical perspective in order to enhance tourism and regeneration knowledge and practice in WHUAs.

At the same time, there are several important limitations that should be considered when interpreting the results. First, the search was limited to Web of Science and Scopus and to English-language records; consequently, regional studies published in other languages or in national repositories, as well as relevant grey literature (reports, theses, local planning documents), were neglected. Second, despite following standard procedures to enhance reliability in inductive content analysis, it includes subjective interpretation during coding and abstraction, which can lead to researcher bias despite efforts to ensure reliability through repeated review. Finally, the search string focused on specific keywords and did not explicitly include related terms such as "rehabilitation" or "renovation," which could have captured additional relevant studies. Future studies should consider expanding database coverage and languages, including grey literature, using multiple coders (with inter-coder checks), and conducting sensitivity analyses with alternative search strings to test the robustness of bibliometric patterns observed here.

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Perceptions of Heat Risk Among Street Vendors, Its Associations With Knowledge and Impacts on Adaptive Measures in a Tropical Indian City

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Abstract
There has been a concerning rise in heatwave-related deaths in India over the past few decades, particularly affecting the informal work sector exposed to high outdoor temperatures. This study aimed to understand how outdoor workers and street vendors in the landlocked tropical city of Nagpur perceive heat risks and how this perception relates to their knowledge and adaptive measures. A cross-sectional study using face-to-face surveys was conducted, introducing a novel Heat Risk Perception (HRP) Index to quantify participants' risk perception. The findings revealed that 70% of street vendors had high HRP, with a mean index score of 0.72. Local knowledge and past heat experiences significantly influenced risk perception, despite gaps in scientific knowledge resulting from limited access to training programs. A strong positive relationship was observed between HRP and adjustments in work routines during hot weather, especially when vendors perceived health risks. This suggest that risk perception is crucial for adopting protective behaviours. Demographic factors did not significantly affect heat risk perception. Notably, 69% of vendors perceived themselves as vulnerable to heat's negative effects, and perceived vulnerability emerged as a significant predictor of high HRP. The findings highlight the importance of risk perception in mitigating heat-related risks among vulnerable populations. The study's results can inform the development of targeted interventions to protect street vendors and outdoor workers from heat-related risks.

Key Words: heat risk perception; extreme heat; heatwaves; adaptation; informal workers

Introduction
The Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC AR6) highlights that we can expect more frequent and intense heat extremes, including heatwaves, with near certainty. These events are likely to have a greater impact on people than most other climate change phenomena (IPCC, 2023). Unlike extreme weather events like floods or earthquakes, which have immediate and visible effects, the risks associated with extreme heat can be less apparent. However, research suggests that extreme temperatures are a significant

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contributor to weather-related mortality around the world (Murray et al., 2020). In India, for instance, deaths from extreme heat surged by 55% between 2000-2004 and 2017-2021 (Romanello et al., 2021). The March 2022 heatwave, the warmest month recorded since 1901 in India, exposed up to 75% of the labour force dependent on heat-exposed labour to potentially life-threatening temperatures (Rajeevan et al., 2023). Given that this sector contributes roughly half of India's GDP, the country is particularly vulnerable to job losses due to heat stress. This vulnerability could lead to around 34 million of the projected 80 million global job losses by 2030 (Woetzel et al., 2020).

Heat risks can be mitigated through adaptation strategies, which require governmental implementation of comprehensive infrastructure plans, early warning systems, and behavioural guidelines (National Disaster Management Authority, 2019). Most Heat-Health Warning Systems (HHWs) are designed to reduce illnesses and deaths related to extreme heat. There's been a lot of research on the quality and content of these warning systems and how they integrate with Heat Action Plans (HAPs) (Li et al., 2022). However, their effectiveness is less studied. The success of HHWs depends heavily on the community's willingness to respond to these warnings (Toloo et al., 2013). It turns out that perception plays a crucial role in shaping this response. Heat risk perception (HRP) reflects how concerned someone is about the negative effects of extreme heat. This perception can influence how well people understand the risks and whether they take steps to protect themselves, making it a key factor in predicting protective behaviours (Li et al., 2024).

Several studies have explored the public's perception and attitudes towards extreme heat. Some researchers have conducted large-scale surveys to understand how people across entire nations view the risks associated with heat (Beckmann & Hiete, 2020; Howe et al., 2019; Li et al., 2024; Parichehr Shamsrizi et al., 2023; Schoessow et al., 2022). Others have focused on smaller regions or specific cities to gain insights into local attitudes and behaviours (Liu et al., 2013; Rauf et al., 2017; Williams et al., 2018; Akompab et al., 2013; Ban et al., 2017; Dong et al., 2024; Hass & Ellis, 2019; Heidenreich & Thieken, 2021; Huang et al., 2017; Lane et al., 2014; Madrigano et al., 2018; Suldovsky et al., 2024; Maheshwari, 2022). National studies provide a broad overview of how a country's population perceives heat risks. However, focusing on smaller areas or specific cities offers more detailed and localized insights. This is important because climate, demographics, work practices, and individual adaptations can vary significantly from one region to another. Local studies help identify the unique challenges and risk factors related to extreme heat in specific populations (Han et al., 2021). Different methods have been used to assess heat risk perception (HRP). For instance, a study in the U.S. used a heat risk perception index, scored from 0 to 100, to gauge how people view the risks and health impacts of heat waves (Howe et al., 2019). Another study in China looked at risk perception, adaptation behaviours, and heatstroke among participants using structured questionnaires and statistical analysis (Liu et al., 2013). These approaches, including surveys, questionnaires, and statistical analyses, have been instrumental in measuring HRP. They help identify what influences people's perceptions, understand why people change their behaviours in response to heat, and evaluate awareness of heat-related risks across different populations and locations.

Extreme heat affects different groups in various ways, making it essential to understand its impact on vulnerable populations. Street vendors are especially at risk because their work is physically demanding, they often lack access to shade, and they have limited cooling options. These conditions increase their chances of suffering from heat-related illnesses and can negatively impact their productivity and earnings (Kjellström et al., 2019; Singh et al., 2019;

Luber & McGeehin, 2008). HRP among vulnerable groups has been extensively studied. This includes outdoor workers in sectors like construction, waste disposal, and agriculture, as well as migrant workers and the homeless (Bonafede et al., 2022; Elshamy et al., 2024; Putra et al., 2024; Yovi et al., 2023; Han et al., 2021; How et al., 2021; Xiang et al., 2016; Lohrey et al., 2021; Messeri et al., 2019; Permatasari et al., 2023; Iswarya et al., 2024; Robertson et al., 2024). A study in Hanoi found that street vendors, as a distinct income group, may have varying levels of knowledge about heat impacts and preventive measures, which can influence their risk perceptions (Lohrey et al., 2021). Despite the frequent occurrence of heat waves in India, no studies, to our knowledge, have specifically examined heat risk perception. This gap in the literature highlights the need for more research to understand the challenges these vulnerable groups face in managing heat-related risks and to develop targeted interventions.

The present study has the following objectives:

(a) To measure and analyze heat risk perception among outdoor workers and street vendors in Nagpur using a HRP index.
(b) To investigate how current knowledge, awareness, sociocultural factors, and demographic characteristics shape heat risk perceptions and influence adaptive behaviours.

By pursuing these objectives, the study aims to fill a crucial knowledge gap by examining how people understand, perceive, and adapt to heat waves, and by identifying the key factors that influence these aspects. The findings of this research can inform similar studies in areas experiencing extreme heat waves and contribute to making Heat-Health Warning Systems (HHWs) more effective. Ultimately, this may help reduce illnesses and deaths related to extreme heat and strengthen Heat Action Plans (HAPs). This study is one of the first in India to focus specifically on heat risk perception among informal workers and street vendors. Data collection for this study involved a survey administered in a specific area, utilizing a questionnaire as the primary research method. Due to the lack of previous research on subjective responses to heat-related inquiries among informal workers, there is no pre-existing documentation or secondary data available for comparison or validation.

Study Area

The study was conducted in Nagpur, an important urban area in central India. The city experiences a tropical savanna climate (Aw), with temperatures varying from 48 degrees Celsius in summer to 6 degrees Celsius in winter. Extreme temperatures are experienced during the month of May, and those days are locally referred to as 'Nava Tappa'. The city has also recorded 246 heat wave days annually in 50 years from 1969 to 2019 (IMD), making it an appropriate location to conduct the study.

The workforce participation ratio in Nagpur city is at 37%, with male workers contributing around 78% and female workers 22%, to the total workforce. Street vending is an indispensable economic activity in the city as is the case in most urban India, with about 90,000 street vendors or hawkers in the city in 2015, accounting for about 10% of the workforce. The informal markets in Nagpur can be classified into three main types: weekly markets, daily markets serving the city or a part of the city, and neighbourhood cluster markets. These markets

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can be further categorized as city level, sub-city level, or neighbourhood level markets based on the number of units, scale, and year of establishment. The study seeks to include all types of markets with an active presence of street vendors to gather a holistic data pool, as shown in Figure 1.

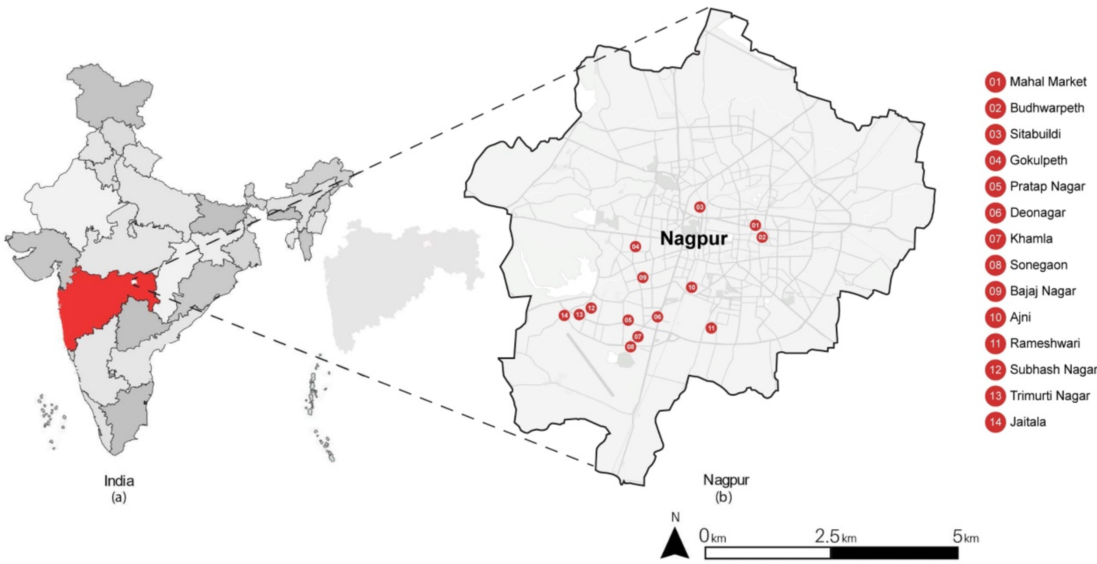

Figure 1. Study Area

Data and Methods

In this study, Heat Risk Perception (HRP) refers to how individuals perceive, assess, and respond to extreme heat risks according to their beliefs, awareness, and attitudes. The study introduces a Heat Risk Perception Index, ranging from 0 to 1, which is derived from questionnaires that capture various aspects such as the likelihood, severity, worry, concern, and fear reported by individuals regarding their own health and economic prospects. Through statistical analysis, the study also reveals how sociodemographic factors, knowledge, and past experiences with heatwaves and associated illnesses influence these perceptions.

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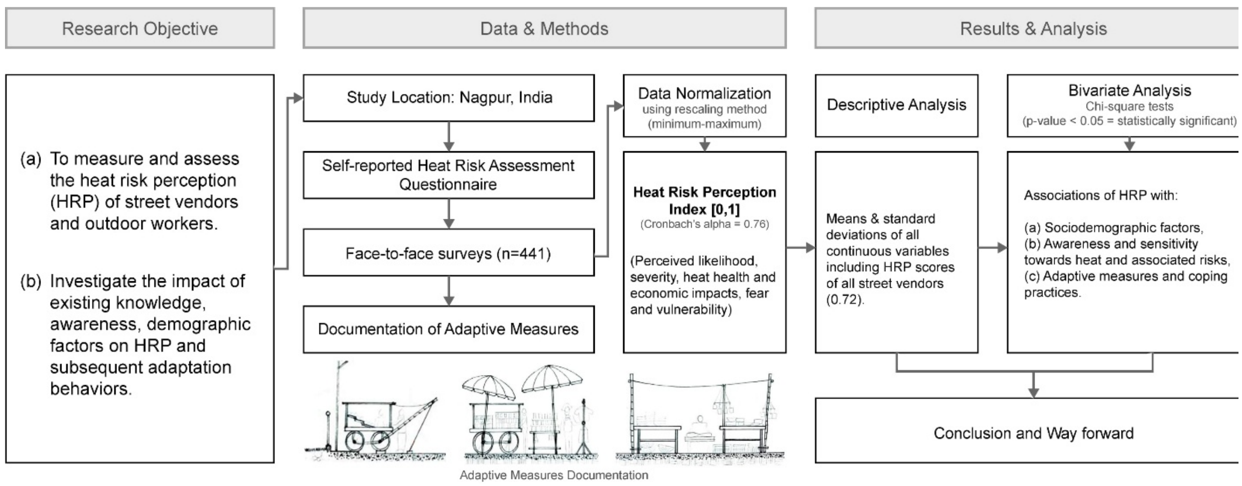


Figure 2. Study Methodology

Questionnaire Design

A questionnaire was specially created drawing on established research on heat risk perception and its known predictors. This questionnaire was designed to self-report perceived heat risk, specifically focusing on the experiences of street vendors during heatwaves (Ban et al., 2017; Huang et al., 2017). The questionnaire was divided into four sections, building on previous research but adapted to better address the unique challenges faced by street vendors.

The sociodemographic section of the questionnaire gathered information on age, gender, education, family structure, migrant status, and any pre-existing health conditions. To assess knowledge and awareness about heat, we asked participants about their past experiences with heatwaves, their perceptions of rising temperatures, how often they check weather forecasts, whether they have participated in heat-related training, and if they have received heat warnings. Additionally, respondents were asked to share their past experiences with extreme heat, any heat-related illnesses they encountered at work, and the measures they took to combat these illnesses.

Given that risk perception is multifaceted, the questionnaire used various risk characteristics to measure it. Participants rated the likelihood and severity of heat waves and their impacts on Nagpur using a five-point Likert scale, considering both the likelihood and intensity of these events. They were also asked about their worries related to the health impacts of heat, particularly focusing on risks to themselves, their families, and their communities. Individuals rated their personal risk on a five-point Likert scale, where '1' represented 'Low' and '5' represented 'Severe,' with higher scores indicating a higher perceived risk. For family and community risks, respondents simply answered "Yes" or "No" to express their concerns. Similarly, concerns about the impact of heat on expenses, productivity, and employment were answered with “Yes,” “Maybe,” or “No.” Respondents also indicated their fear of adverse health effects of heat by selecting “Yes,” “Maybe,” or “No”.

Finally, participants were queried whether they believed heat posed a risk to their lives, with the goal of determining whether they considered themselves vulnerable to extreme heat (ref. Appendix A). The Heat Risk Perception Index (Cronbach’s alpha = 0.76) was derived by combining responses from a survey tool consisting of 10 questions. These questions explored perceptions of the adverse effects of extreme heat, including its likelihood, severity, health-related concerns and fears, economic implications, and overall vulnerability. Additionally, questions about adaptive strategies and protective actions centred on physical measures and lifestyle changes implemented during extreme heat events, along with their perceived effectiveness.

Data Collection and Processing

The research employed in-person surveys conducted in May 2022, coinciding with a heatwave across much of India. Respondents were informed about the study's objective, and verbal consent was obtained before starting the survey. The questionnaires were administered in the respondent's preferred language, and each survey took approximately twenty minutes to complete. In total, 441 completed questionnaires used in the final data analysis.

The survey comprised questions with various response formats, including a five-point Likert scale (ordinal) and nominal choices like "Yes," "Maybe," and "No" or simply "Yes" and "No." To ensure consistency, indicator values measured in different units were standardized to a common scale using a min-max normalization approach. This adjusted the values to a standardized range of [0,1]. To calculate the Heat Risk Perception (HRP) index score, the mean of all ten indicator questions was computed for each respondent.

Statistical Analysis

Data collected was exported to Excel, which acted as the main database for conducting descriptive and bivariate analyses using R and RStudio (RStudio Team, 2020; R Core Team, 2020). The 'vcd' package (Meyer et al., 2022) was utilized to create mosaic plots that visualized Pearson residuals. Descriptive analysis summarized all sections of the questionnaire and calculated means and standard deviations for continuous variables. Bivariate analysis involved applying Chi-square tests, adjusted for expected cell frequencies of five or fewer, to investigate relationships among categorical variables such as socio-demographics, knowledge, adaptation, and risk perception. This process aimed to determine key influencing factors, with associations considered statistically significant if the p-value was less than 0.05.

Results and Analysis

In total, 441 street vendors and informal workers participated in the survey, with 83.4% being men and 16.6% women—a gender distribution broadly reflective of the city's overall workforce composition. The respondents had an average age of 39.56 ± 12.41 years, with 42% falling within the 36–50 age group. Many had finished only high school (29.7%), while 13% lacked formal education. Among those surveyed, 28% had migrated to Nagpur for work, predominantly men (87.1%). The survey found that 72.3% of respondents had family members under 15 or over 65 years old, suggesting they were primary caregivers for individuals more vulnerable to extreme heat (Romanello et al., 2021; Stanberry et al., 2018). Furthermore, 11.6% had a pre-existing chronic illness, most of whom were aged 36-50 (45%). Most of vendors worked outdoors for over 5 hours daily, and 62.8% found their work physically strenuous. Nearly half of the individuals surveyed (47.8%) had encountered heat illnesses while working, including exhaustion, rashes, and even stroke. Common symptoms reported included tiredness, headache, dizziness, heavy sweating, and thirst (Table 1). Coping strategies employed by individuals included increasing fluid intake, taking breaks in shaded areas, and cooling off by splashing water. It was noted that vendors tended to seek medical attention only after experiencing severe symptoms.

Table 1. Common heat-health symptoms and coping strategies

% of respondents who reported heat-illnesses	Top heat-related symptoms reported	% of all reported illnesses	Top Heat Coping Strategies
47.80%	Tiredness or Weakness	16.70%	• Resting in shaded areas • Increasing fluid intake • Taking regular breaks and rest. • Taking days off. • Cooling down by moving to shaded areas or splashing water on the body. • Consulting doctor.
	Feeling Hot	13.60%	
	Heavy Sweating	12.30%	
	Feeling Thirsty	11.60%	
	Dizziness	11.10%	
	Headache	10.70%	
	Heat Rash	6.70%	
	Nausea or Vomiting	5.40%	

Knowledge and Awareness

Most vendors (76.4%) were familiar with heatwaves, but only a few could specify the temperature threshold for declaring a heatwave in the city. A large majority of vendors were aware of the local term for extreme heat period 'Nava tappa', showing a shared understanding among the community. The study also found that majority of the street vendors (68%) had previously encountered heatwaves, and 85.3% believed that summers had become hotter over time. They attributed the rise in temperatures to the building of concrete roads, decreased tree coverage, and pollution in the city.

El-Shafei et al. (2018) suggest that training and education are crucial in preventing heat-related illnesses and injuries. However, 96% of vendors did not have access to such programs. Only 48% received heatwave warnings through sources like newspapers, internet, TV/radio etc. Despite this, 13% of respondents were not concerned about these warnings because they had experienced extreme heat for many years. Most vendors (70%) did not check the weather forecast daily due to the belief that it was unnecessary, as work had to proceed regardless. Additionally, not all vendors possessed smartphones, and newspapers were delivered after they had already left for work. As a result, many vendors were left unaware of impending extreme heat conditions, putting them at risk of heat-related illnesses and accidents.

Heat Risk Perception

The research evaluated heat risk perception scores of participants on an index [0,1], where higher scores denoted greater perceived risk. Those with elevated HRP scores were more likely to: (a) Anticipate a higher probability of heatwave occurrences, (b) Acknowledge the severe nature of heatwaves in the city, (c) Worry about the adverse effects of heat on their personal, family, and community health, (d) Worry about impact of heat on expenditure, employment, and work productivity, (e) Be fearful of heat-related health issues, and (f) Perceive themselves as vulnerable to extreme heat.

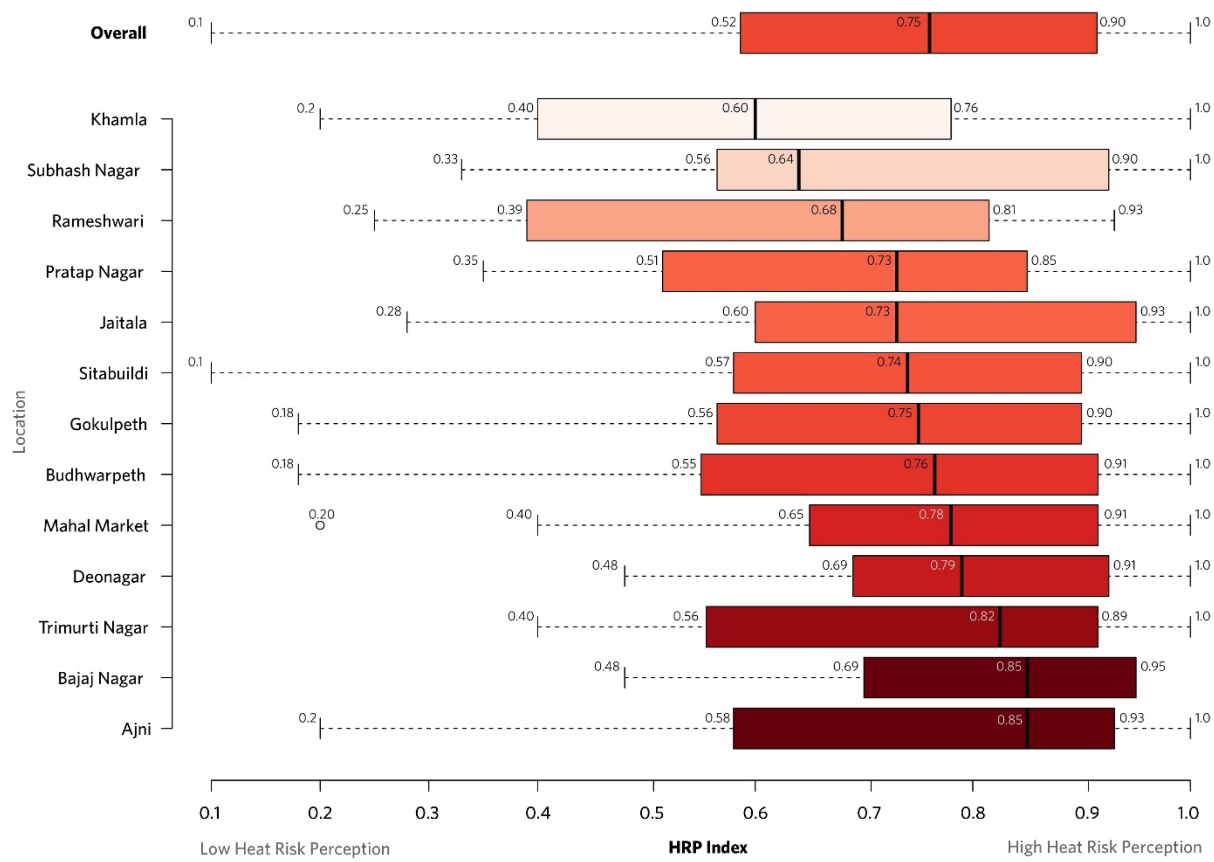


Figure 3. Boxplot of market-wise heat risk perception.

The average HRP Index across all city markets was 0.72, although minor differences in the mean HRP were noted depending on the location (see Figure 3). Males had a slightly higher HRP (0.721 ± 0.22) compared to females (0.708 ± 0.03). Cart pullers had the highest HRP score (0.800 ± 0.21), while tea vendors demonstrated the lowest score (0.671 ± 0.12). This indicates a connection between HRP, sun exposure, and physical demands of the job (see Table 2). Additionally, those who had migrated to the city tended to have a higher HRP, as did individuals with family members under 15 or over 65.

Table 2. Mean of HRP Index across sociodemographic characteristics

Sociodemographic Characteristics	Category	HRP Score (Mean)	Sociodemographic Characteristics	Category	HRP Score (Mean)
Gender	M	0.720	Occupation	Beverage Cart	0.671
	F	0.718		Flower Seller	0.684
Age	≤ 20	0.788		Puncture Repair Shop	0.689
	21-35	0.719		Vegetable Seller	0.702
	36-50	0.723		Clothing Accessories Vendor	0.734
	51-65	0.708		Autorickshaw Driver	0.753
	66-80	0.679		Fruit Vendor	0.759
Highest Education	No Formal Education	0.699		Clothing Seller	0.760
	Class 4	0.678		Metal Items Seller	0.797
	Class 7	0.737		Handcart Puller	0.800
	Class 10	0.723	Migration Status	Migrant	0.733
	Class 12	0.721		Non-migrant	0.714
	Undergraduate	0.752	Chronic Illness	Yes	0.722
	Postgraduate	0.566		No	0.719

Many sellers were worried about heatwaves, with 63% believing that Nagpur faces them nearly every year and 70.3% deeming them highly severe. About 47% thought heatwaves were dangerous to their well-being, 74% expressed concern for their families' health, and 57% were worried about the well-being of their community. Several vendors refrained from disclosing their own heat-related health illnesses, though 37% confirmed experiencing at least one. Financial constraints prevented vendors from taking time off during heatwaves, with nearly three-quarters of them (74%) experiencing a decrease in employment and productivity, impacting their earnings. Furthermore, vendors encountered increased costs at both work (64.9%) and home (77.6%) in the summer due to expenses related to water, shading, and cooling techniques. To manage, more than a third switched jobs based on the season and some, even during the day.

Overall, based on the self-assessment, almost 70% of vendors considered themselves vulnerable and at risk to the negative impacts of extreme heat.

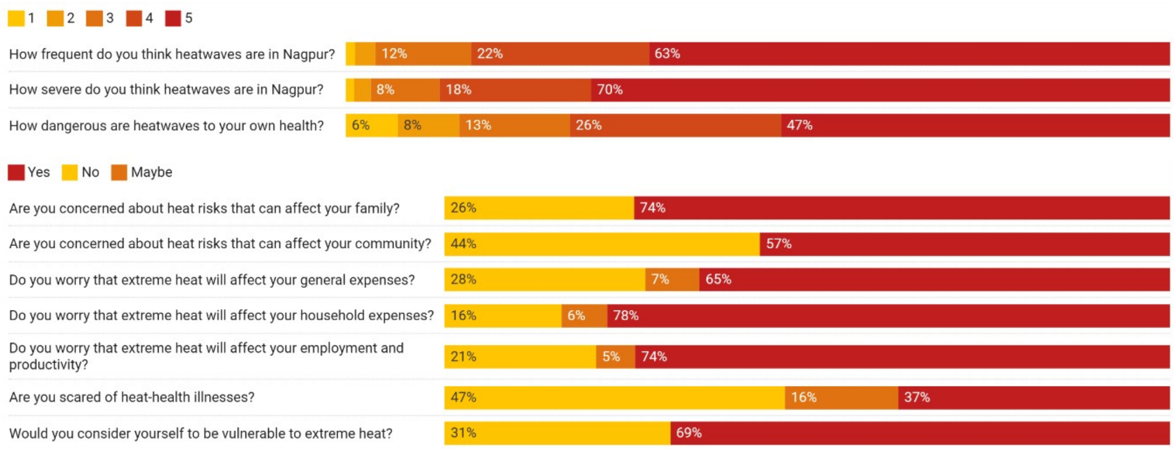


Figure 4. Heat risk perception responses

Adaptive Measures

The study identified two types of adaptive measures: physical adaptations in the workplace and lifestyle changes in behaviour. Around 43% of street vendors believed it was necessary to adjust their work habits to prevent heat illnesses, and 55% consistently implemented measures to adapt when stepping out of their homes (Figure 5). Common lifestyle adaptive measures included staying well-hydrated, wearing light-coloured, full-sleeved cotton clothing, seeking shade or cooler areas, and modifying dietary habits. Furthermore, some individuals managed to avoid the midday heat by carefully planning outdoor activities, altering their work hours (extending night shifts and shortening daytime shifts), and taking extended lunch breaks. A significant number of vendors (76.2%) made changes to their work environment, with the most popular adjustment being the installation of a green sunshade HDPE net (52%). Others opted for garden or rain umbrellas (14%), while some utilized gunny bags (11.3%) or a table fan if there was access to electricity.

Some individuals failed to take necessary precautions to avoid heat-related illnesses for various reasons. The majority of them (63.9%) were used to hot weather conditions and did not feel the need to adapt. Another significant portion (30%) lacked the capability to change their behaviour to prevent heat-related issues. Only a small percentage believed that heat waves did not pose a threat to them (5.3%) or that the weather was not sufficiently hot (2.4%). Vendors who sold goods that were prone to damage or decay from heat focused mainly on safeguarding their products by ensuring they were kept in the shade, rather than prioritizing their own protection.

Figure 5. Adaptive measures responses

Associations Between Heat Risk Perception and Sociodemographic Characteristics, Knowledge, and Adaptive Measures

This section investigates how street vendors' heat risk perception is related to their sociodemographic characteristics, heat wave knowledge, and adaptive measures.

Sociodemographic Characteristics

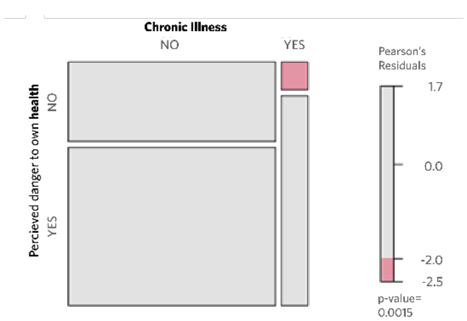
The study found that women were more inclined than men, to view themselves as vulnerable to extreme heat ($\chi^2(1, N = 441) = 12.321, p < 0.001$). Women also expressed greater concern about general and household expenses. However, factors such as age, occupation, education, and migrant status did not show significant associations with HRP (ref. Table 3).

Table 3. Pearson Chi-Squared test results for HRP and Sociodemographic factors

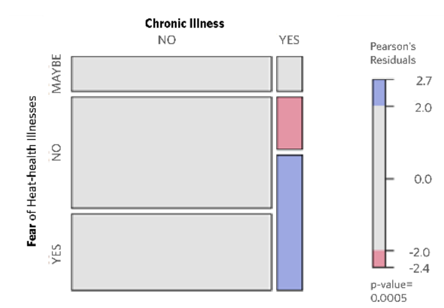
Pearson Chi-Square Tests											
Socio-demographic Characteristics	HRP Factors	Frequency	Severity	Concern (Personal Health)	Concern (Family Health)	Concern (Community Health)	Fear (Heat Illnesses)	Worry (General Expenses)	Worry (Household Expenses)	Worry (Employment& Productivity)	Perceived Vulnerability
Gender	Chi-square	5.096	7.277	9.010	3.103	3.072	5.299	6.763	8.310	1.499	12.321
	Sig.	0.278	0.122	0.061	0.078	0.080	0.071	**.034***	**.016***	0.473	**.000***
Age	Chi-square	17.466	49.402	30.516	18.161	7.234	11.380	14.979	7.661	8.178	8.231
	Sig.	0.356	-	-	-	0.124	0.181	-	-	-	-
Education	Chi-square	24.110	21.643	28.838	8.356	6.063	21.802	9.096	8.958	17.346	8.344
	Sig.	0.455	0.601	0.226	0.213	0.416	-	0.695	0.707	0.137	0.214
Chronic Illness	Chi-square	3.167	3.175	8.456	6.128	7.641	15.150	3.531	3.826	1.336	10.032
	Sig.	0.53	0.529	0.076	**.013***	**.006***	**.001***	0.171	0.148	0.513	**.002***
Migration Status	Chi-square	9.062	6.616	8.403	0.413	0.414	1.022	1.480	0.884	0.344	0.322
	Sig.	0.06	0.158	0.078	0.520	0.520	0.600	0.477	0.643	0.842	0.571

*. The Chi-square statistic is significant at the $p < 0.05$ level.

The study found that respondents with family members under 15 or over 65 years old expressed greater concern about heat-health risks in their community ($\chi^2(1, N = 441) = 5.461$), and were more likely to be fearful of heat-health issues ($\chi^2(2, N = 441) = 7.108, p = 0.029$). Additionally, pre-existing chronic illness emerged as a significant factor influencing heat risk perception. Individuals with chronic conditions exhibited higher levels of concern about the impacts of heat on their families ($p = 0.013$) and communities ($p = 0.006$), besides a heightened fear of heat-related illnesses ($p = 0.001$) and a greater sense of vulnerability to heat risks ($p = 0.002$) (see Figures 6 and 7).

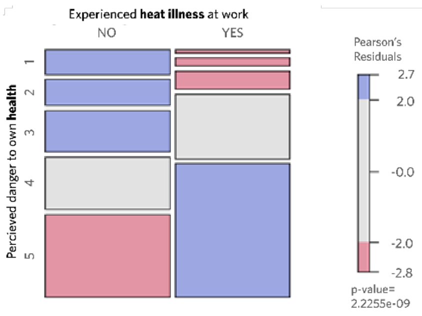


(6A)

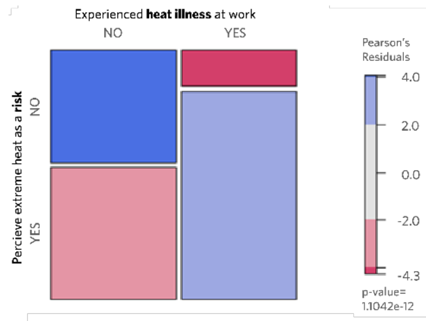


(6B)

Figure 6. Mosaic plot illustrating the association between pre-existing chronic condition and perceived personal health risk (6A) and fear of heat-related illnesses (6B)



(7A)



(7B)

Figure 7. Mosaic plot illustrating the connection between experience of heat illness at work and perceived personal health risk (7A) and considering extreme heat as a risk (7B).

Knowledge

According to studies like Iorfa et al. (2020) and Ning et al. (2020), knowledge acquired through formal education or practical experience has the potential to prompt individuals to develop a more pragmatic understanding of risk, facilitate the appropriate assessment of potential losses, and devise strategies to prevent or alleviate adverse consequences that could emerge. Our findings showed that vendors familiar with heatwaves reported a significantly higher perceived likelihood ($p < 0.001$) and severe nature ($p < 0.001$) of heatwaves in the city. Similarly, prior exposure to heatwaves impacted the perception of heat risk by influencing factors such as perceived probability and intensity. Vendors who acknowledged the increased temperature were more prone to perceiving a higher heat risk. On the other hand, participants who did not perceive a rise in temperature were significantly less likely to view themselves at risk from the adverse impacts of extreme heat, highlighting another factor influencing perceived risk. Additionally, a history of heat illness at work emerged as a key predictor of heat risk perception, affecting nearly all risk factors. These factors included personal health concerns, worries about family and community, heightened health fear, and worries about economic and employment impacts (ref. Figure 7).

Precautionary actions, like tracking weather advisories, were linked to heightened concerns for family ($p = .047$) and community ($p = .013$) health, along with a greater fear of heat-related health issues ($p = .001$). This suggests that individuals with these concerns were more inclined to take preventive measures. Heat warnings led to elevated levels of concern ($p = .031$) and fear ($p < .001$) regarding the health impacts of heat waves. Moreover, the study revealed that individuals who had experienced previous heat-related illnesses themselves were significantly more inclined to heed heat warnings and implement precautionary measures to safeguard their own well-being ($p = .015$). Due to limited availability of training and awareness programs, their impact could not be properly assessed. However, individuals who had undergone heat-related training showed higher concerns and fears about heat-related health issues compared to those who had not received such training.

Adaptive Measures

Heat risk perception was associated with modifications in work routines during hot weather, particularly when vendors felt their personal ($p = .007$), family ($p < .001$), or community health ($p = .001$) was at risk, along with feeling vulnerable ($p = .014$). Vendors who thought they should modify their work habits were more inclined to proactively adopt adaptive behaviours. These behaviours included changing their routine on receiving a heat alert ($p < .001$) and implementing protective measures while outdoors ($p < .001$). Those who viewed heat as a threat to their employment or productive work were more inclined to respond to heatwave warnings ($p = .016$), resulting in a decreased likelihood of going outdoors without adaptive measures. Additionally, vendors concerned about heat-related illnesses for themselves ($p = .019$) or their family ($p < .001$) commonly took protective actions like wearing light-coloured clothing, using headgear, staying hydrated, and were more likely to modify their work environment (see Figures 8 and 9). Overall, the research found that HRP and adaptive measures were significantly associated.

Figure 8. Vendors engaging in adaptive behaviours

Figure 9. Vendors not engaging in adaptive behaviours

Discussion

In the study, about 70% of the street vendors saw extreme heat as a risk to their health, employment and productivity with a mean HRP score of 0.72. Since this is one of the first HRP studies to specifically examine street vendors, direct comparisons are not appropriate; however, the risk perception percentage is higher than that reported in earlier studies conducted on citizens in urban and peri-urban Pakistan (57% and 66%, respectively), and lower than that of Delhi NCT (75.6%), Nanjing (87.6%) and Guangdong (85.2%) (Huang et al., 2017; Liu et al., 2013; Rauf et al., 2017; Maheshwari, 2022). The relatively lower percentage of street vendors who perceive heat risk, compared to other citizens, could be due to a few key factors. Regular exposure to extreme heat at work may have made them less sensitive to it. Additionally, the lack of job alternatives and financial pressures might force them to continue working in hot conditions, despite the risks.

Research has shown that HRP varies among different demographic groups, with factors like age, gender, race, and income level playing significant roles (Beckmann & Hiete, 2020; Madrigano et al., 2018). Additionally, education and prior knowledge have been shown to affect HRP levels (Ban et al., 2017; Liu et al., 2013; Rauf et al., 2017; Williams et al., 2018). Occupational exposure to extreme heat can also affect individuals' risk perceptions and behaviours (Liu et al., 2013). In our study, male vendors had a slightly higher HRP score (0.721 ± 0.216) compared to female vendors (0.708 ± 0.027). This finding contrasts with previous studies in Australia (Akompab et al., 2013), China (Liu et al., 2013), Pakistan (Rauf et al., 2017), and the USA (Howe et al., 2019), whose findings generally showed that women had a higher perception of heat risk. However, our study did find that women were more inclined than men to view themselves as vulnerable to extreme heat. The unequal representation of males and females among the participants in our study could potentially introduce bias into the results. Additionally, the study did not find any significant associations between HRP and age, education, occupation or migrant status. In other words, street vendors responded similarly regardless of their sociodemographic backgrounds. These findings align with those of Ban et al. (2017), where the majority of demographic variables did not impact HRP. The family background, however, impacted HRP, particularly for those with an at-risk family member. This aligns with findings by Akompab et al. (2013), which suggested that concern for the well-being of someone you live with can heighten the perceived heat risk. Additionally, various studies, including one by Han et al. (2021) on construction workers, have shown that individuals with chronic diseases tend to view heat as a greater risk (Beckmann & Hiete, 2020; Maheshwari, 2022). Our study supports this observation, as respondents with pre-existing chronic illnesses were more likely to be fearful of heat-related health issues.

Even though occupational heat exposure and chronic health issues can elevate HRP, lack of autonomy and feelings of helplessness can result in workers giving heat safety a lower priority while on the job (Hass & Ellis, 2019; Liu et al., 2013; Singh et al., 2019; Zander et al., 2017). For example, many workers felt that weather alerts had minimal impact on their daily routines since they had to work regardless of the forecast. As a result, they often didn't check heatwave information and assumed their current knowledge was sufficient. However, those who had access to weather reports, heat warnings, and training programs tended to have a higher HRP. Our study found that past experiences with heatwaves influenced how people perceived heat risk, making them more concerned about the likelihood and severity of future events. The study also confirmed that previous experiences can motivate adaptive measures, as reported in the findings of other research (Akompab et al., 2013; Ban et al., 2017; Esplin et al., 2019; Hass & Ellis, 2019; Rauf et al., 2017; Zander et al., 2017). This aligns with the observation that individuals who have experienced physical risks tend to have higher psychological risk perceptions and are more likely to engage in adaptive behaviours (Ban et al. 2019; Musacchio et al., 2021). Though, outdoor workers being exposed to higher daily risks may cause them to underestimate the dangers of heat exposure and view them as less severe than other hazards (Hass & Ellis, 2019; Lane et al., 2014; Permatasari et al., 2023; Williams et al., 2019). Our research revealed that many vendors have grown accustomed to the heat and don't perceive it as a novel risk anymore. This is worrisome because it reduces their awareness of the significantly increased heat risk because of factors such as the urban heat island effect and climate change (Coleman, 2022; Reid et al., 2009).

The study found that 66% of respondents changed their lifestyle and engaged in protective behaviours to lower the risk of heat impacts, while 76% of respondents took physical adaptive measures at their workplace. Lifestyle measures may be more popular because they are easier to implement (such as changing work hours, wearing summer scarves, and staying adequately hydrated) and do not require much additional monetary investment. However, our study found that migrant workers were less likely to engage in either lifestyle adjustments or workplace modifications. The study by Messeri et al. (2019) provides insights into this, suggesting that migrants perceive lower levels of heat and exhibit reduced productivity decline in comparison to local workers, potentially due to a higher threshold for heat tolerance or a poorer heat risk perception.

The cross-sectional survey approach used for the study enabled direct engagement via face-to-face questionnaires during an active heatwave, which captured immediate perceptions and reduced recall bias. It also allowed to simultaneously document existing adaptive measures and coping strategies. However, the gender imbalance in the data limits generalizability and highlights the structural barriers in accessing female vendors. The comprehensive HRP Index effectively combined cognitive and affective dimensions with acceptable internal consistency (Cronbach's alpha = 0.76). The study used an unweighted mean of normalized indicators, assuming that each indicator contributes equally to the overall HRP construct. This approach was optimal given the research objectives and target population constraints, though future research could improve by assigning weights based on relative importance to the latent construct.

Conclusion

The research evaluated how 441 outdoor workers and street vendors in Nagpur perceive heat risks, using HRP scores on an index scale ranging from 0 to 1. The HRP index showed a generally high heat risk perception, with an average score of 0.72. Perceived vulnerability was identified as the key predictor of risk perception, significantly influenced by individual's previous experiences with heat. The study highlighted several important predictors of heat risk perception, such as acknowledging increasing temperatures, past negative experiences with heatwaves, and fear of heat-related illnesses. Vendors considered health risks as the primary factor in assessing overall heat risk. Fear of heat illnesses was found to be a strong motivator for positive behaviour change. Consistent with previous studies such as Ban et al. (2019), Hass & Ellis (2019), and Liu et al. (2013), our findings showed that HRP and the uptake of adaptive behaviours were significantly associated. This study confirms that heat risk perceptions are important predictors of adaptive measures for street vendors, just like they are for other demographic groups. The study determined that specific sociodemographic factors, such as chronic illnesses and vulnerable family members, influence heat risk perception (HRP). Most sociodemographic factors, however, were not significantly associated with heat risk perception. It also found that knowledge-related aspects, including training and awareness programs, positively impact on HRP. It also follows that those with less access to relevant information are less likely to engage in adaptive behaviours. However, conventional education alone proves inadequate and less effective, highlighting the need to explore alternative approaches tailored to the specific needs of vendors. These approaches should also incorporate local wisdom and pre-existing knowledge within the community.

Nagpur, like many tropical cities, has long experienced high temperatures, which has led some vendors to become acclimated, consequently lowering their perception of heat risk. Although initiatives like the Heat Action Plan (HAP) are in place, risk communication campaigns often provide basic advice, such as increasing water intake, staying in the shade etc. Vendors may not find this advice practical or helpful. While multiple awareness workshops could be beneficial, their effectiveness hinges on the public's risk perception. Our study provided evidence that vendors recognizing heat as a risk are more likely to adopt mitigation measures, thereby reducing the negative health and economic impacts of heat exposure. However, vendors infrequently adopting physical (24%) or lifestyle (14.5%) measures face increased vulnerability. This finding underscores a significant gap in addressing heat-related issues among vendors and highlights the need for enhanced training and education efforts targeting this vulnerable group. Simply improving knowledge about heat through formal training may not substantially increase preventive behaviours. Health campaigns may achieve greater success if they consider both cognitive and affective risk perceptions (Shamsrizi et al., 2023), since these perceptions are moulded by personal experiences, cultural beliefs, social influences, and psychological factors (Lerner & Keltner, 2001; Slovic & Peters, 2006). Neglecting this issue may lead to higher mortality and morbidity rates. Our study suggests that enhancing vendors' heat risk perception can improve their response. However, it is crucial to interpret this result with caution, as heightened risk perception does not always translate into precautionary behaviour. Higher risk perception is more likely to lead to such actions when individuals believe that practical safety measures are available and within their capability to implement.

This research provides actionable insights for climate adaptation policy by quantifying heat risk perception among a previously understudied vulnerable population. The HRP Index offers a standardized measurement tool that could inform targeted interventions, though its effectiveness requires validation across different contexts and seasons. The study documents that 47.8% of street vendors experience heat-related illness, providing quantified evidence for local health authorities to prioritize heat-health interventions relevant to sustainable development goal (SDG) 3 targets on environmental health risks. The study's identification of local knowledge systems and existing adaptation practices provides entry points for policy makers to build upon existing community knowledge rather than imposing external solutions. Evidence that 76.2% of vendors already modify their work environments suggests policy support for low-cost cooling solutions (shade nets, fans) could be effective. It also points to implementation pathways towards SDG 11, such as urban planning policies that mandate shade structures in informal market areas and development of climate-responsive public space design standards. The research also provides insights for building adaptive capacity among climate-vulnerable populations, an important target of SDG 13. The methodology and findings contribute to knowledge systems for climate action in developing country contexts. However, success in contributing to SDG targets requires robust monitoring systems that may not currently exist for informal worker populations. The informal nature of street vending also creates challenges for systematic intervention delivery.

Further research on heat risk perception among diverse vulnerable populations is essential for developing dedicated Heat-Health Warning Systems (HHWS). Since a single policy may not be suitable for everyone, these insights can help tailor provisions for distinct groups. For instance, older adults might benefit from staying indoors during heatwaves, but this may not be practical for outdoor workers. It's important to note that this study focused on urban street vendors, so its findings may not directly apply to vendors in other regions. Our study highlighted that HRP is extremely subjective and shaped by various factors, including local conditions. To better understand how specific vulnerable groups perceive heat risk in their regions, localized studies are essential. Results from comparable studies in rural or peri-urban locations might yield different insights, contributing to a more comprehensive understanding of heat risk perception. This study's findings should be considered in light of two limitations. Firstly, a significant portion of the respondents were male workers, which may introduce bias and limit the generalizability of the results to all workers. Secondly, the study did not explore the impact of vendors' income on their heat risk perception (HRP) due to the challenges in obtaining accurate income responses from respondents. Given that income affects the ability to protect oneself from heat and overcome adaptation barriers, it is essential for future studies to explore the income-heat risk perception relationship in depth. Despite these limitations, the study provides valuable insights into heat risk perception among informal vendors and their individual protective responses. It emphasizes the need for impactful behavioural measures and adaptation plans to address the challenges faced by this vulnerable group.

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Appendix A: Questionnaire

Section A. Sociodemographic Information

Q1. Gender

a. Male
b. Females

Q2. Occupation

a. Fruit Vendor
b. Vegetable Vendor
c. Flower Vendor
d. Food and Drinks Vendor (Lemonade. Fruit Juice, Cookies, Snacks, Grains, Spices)
e. Metal Article Vendor
f. Chai/Coffee/Pan Stall
g. Clothes Vendor
h. Clothing Accessories
i. Books, Stationery and Paper
j. Puncture & Repairing
k. Autorickshaw
l. Cart Puller/Handyman/Porters
m. Miscellaneous (Disposables, Barber, Butcher, Cobbler, Band Musician, Pooja Items, Potter, Laundryman, Key Maker, Handmade Items, Mobile Accessories, Home Accessories, Scarp Vendor, Security Guard, Shoe Polish, Tailor)

Q3. Age

a. ≤20
b. 21-35
c. 36-50
d. 51-65
e. 66-80

Q4. Highest Education

f. No formal education
g. Primary School (Till 4th)
h. Middle School (Till 7th)
i. High School (Till10th)
j. Junior College (Till 12th)
k. Undergraduate
l. Postgraduate

Q5. Does your family have children under 15 or elders above 65?

a. Yes
b. No

Q6. Have you migrated to Nagpur?

a. Yes
b. No

Q7. If yes, where are you from?

a. Madhya Pradesh
b. Delhi
c. Rajasthan
d. Bihar
e. Chhattisgarh
f. Karnataka
g. Uttar Pradesh
h. Gujarat

Q8. Do you have any chronic illnesses?

a. Yes
b. No

Section B. Awareness, Sensitivity and Previous Experience (Knowledge of heat and related risks)

Q9. How do you define heat/hot weather?

- □ When the temperature rises above a certain threshold
- □ When changes are needed in normal behaviours or activities
- □ When discomfort is felt
- □ When health effects are experienced

Q10. Do you check the weather forecast daily before leaving your house?

a. Yes
b. No
c. Sometimes

Q11. Have you heard about "heatwaves" in the past?

a. Yes
b. No
c. Maybe

Q12. Have you ever experienced a heatwave?

a. Yes
b. No
c. Maybe

Q13. Do you receive heat warnings?

a. Yes
b. No

Q14. If yes, how did you get this information?

a. Past Experience
b. Word of mouth
c. Newspaper
d. Internet
e. TV/ Radio
f. Mobile broadcast

Q15. Did you ever have access to a training/awareness program for heat-related risks?

a. Yes
b. No

Q16. In the past several years, did you feel the weather was hotter than before?

a. Yes
b. No
c. I don't know

Q17. Have you ever experienced a heat illness at work?

a. Yes
b. No

Q18. If yes, which have you experienced?

- □ Do not remember
- □ Heavy Sweating
- □ Cold, pale, clammy skin
- □ Heat Rash
- □ Nausea or vomiting
- □ Muscle cramps
- □ Tiredness or weakness
- □ Dizziness
- □ Headache
- □ Fainting
- □ Feeling hot
- □ Thirsty
- □ Cough
- □ Other:

Q19. If yes, what measures did you take to combat your heat-related illness?

Section C. Heat Risk Perception Variables

Perceived Aspect	Question	Response
LIKELIHOOD	How frequent do you think the heatwaves are in Nagpur?	• 1 (Never) • 2 (Rarely) • 3 (Sometimes) • 4 (Often) • 5 (Always)
SEVERITY	How severe do you think the heatwaves are in Nagpur?	• 1 (None) • 2 (Very Mild) • 3 (Mild) • 4 (Moderate) • 5 (Severe)
CONCERN (HEALTH)	How dangerous are heat waves to your own health?	• 1 (Low) • 2 (Moderate) • 3 (Considerable) • 4 (High) • 5 (Severe)
	Are you concerned about heat-related risks that can affect your family?	• Yes • No
	Are you concerned about heat-related risks that can affect the community?	• Yes • No
CONCERN (ECONOMIC)	Do you worry that extreme heat will affect your general expenses?	• Yes • Maybe • No
	Do you worry that extreme heat will affect your household expenses?	• Yes • Maybe • No
	Do you worry that extreme heat will affect your employment and productivity?	• Yes • Maybe • No
FEAR (HEALTH)	Are you scared of heat-health illnesses?	• Yes

		• Maybe • No
VULNERABILITY	Would you consider yourself to be vulnerable to extreme heat?	• Yes • No