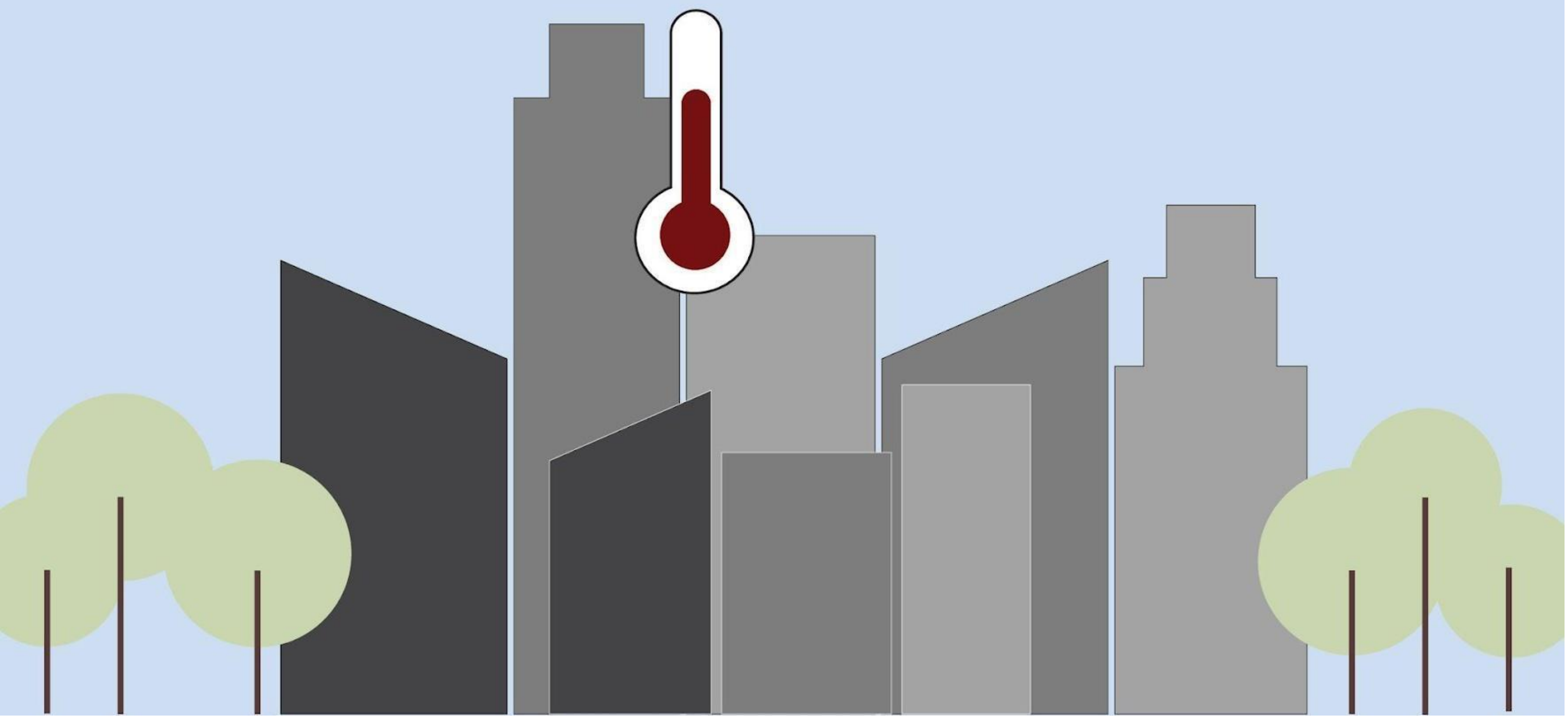
URBAN HEAT ISLAND IDENTIFICATION AND MAPPING METHODOLOGY



Funded by the European Union

REPUBLIKA HRVATSKA
Ministarstvo prostornoga uređenja, graditeljstva i državne imovine

This document has been created as part of the project "Support for Implementing Green Transition Measures under Croatia's NRRP in Reconstructing Earthquake-Damaged Buildings" (in Croatian: "Potpora provedbi mjera zelene tranzicije u području obnove zgrada oštećenih potresima u okviru Nacionalnog plana oporavka i otpornosti").

The project is funded by the European Union via the Technical Support Instrument (TSI) and implemented by the European Bank for Reconstruction and Development (EBRD) in cooperation with the European Commission's Directorate-General for Structural Reform Support (DG Reform).

Technical support is provided to the Ministry of Physical Planning, Construction and State Assets, Republic of Croatia.

CONTENT

Figure list:

Table list

Matrix list

INTRODUCTION

INTRODUCTION

This document aims to analyse the effects of urban heat islands (hereinafter: UHIs), explore the factors contributing to their creation, and assess their influence on urban space residents and users.

Special attention has been dedicated to the literary sources, focused on regional and national research of the creation, consequences and methods of the mitigation of UHI impact.

This document comprises four main chapters:

- **URBAN HEAT ISLANDS** – term definition, as well as creation and effect analysis
- **IDENTIFICATION AND MAPPING** – review of specialist UHI-focused literature, importance of remote sensing with regard to UHI identification, proposal of identification and mapping methodology adapted to the Croatian context
- **INTENSITY CHANGE SUPERVISION** – defining guidelines for the supervision of UHI intensity change
- **UHI MITIGATION MEASURES** – proposing measures for the mitigation of UHI effects; the measures refer to the development of green and blue infrastructure, space shaping and technology use

GLOSSARY

Glossary of the most important expressions/terms

English term	Croatian translation	Description
Albedo	Efekt albeda	The ability of a surface to reflect sunlight (albedo is a physical value referring to the light reflected from the surface of a body that does not produce light by itself)
Atmospheric urban heat island (AUHI)	Atmosferski urbani toplinski otok	The temperature of the atmospheric layer above an urban area which is higher in comparison to the temperature of the same layer in the surroundings of the city
Boundary layer urban heat island	Urbani toplinski otok prizemnog sloja atmosfere	The temperature of the atmospheric layer at a height of max. 2000 meters in the city which is higher in comparison to the temperature in the surrounding rural areas
Canopy layer urban heat island (CUHI)	Urbani toplinski otok u razini krošanja drveća	Temperature at canopy level (below roof level) in the urban area which is higher in comparison to the temperature at the same level in the surroundings of the city
Climate sensitive urban design (CSUD)	Klimatski osviješten urbanistički dizajn	Urban spatial planning processes which take into account the effects of UHIs
Global warming level (GWL)	Razina globalnog zatopljenja	The level of global temperature increase by the end of the 21st century
Land surface temperature (LST)	Temperatura površine tla (TPT)	Land surface temperature/temperature of the Earth's crust is measured directly or by satellite
Land use/Land cover (LULC)	Zemljišta prema namjeni i pokrovu	Classification of land by use and type of cover (e.g. urban area, forest, agricultural land, water body, etc.)
Representative concentration pathways (RCP)	Predviđena koncentracija stakleničkih plinova	Climate change scenarios predicting four possible concentration pathways (not emissions) of greenhouse gases as a result of climate change
Shared socioeconomic pathways (SSPs)	Globalni pravci društveno-ekonomskih promjena	Set of scenarios predicting socioeconomic pathways which are likely to occur by 2100 due to climate change
Urban heat island (UHI)	Urbani toplinski otok (UTO)	An urbanised area that is significantly warmer than its rural environment as a result of artificial infrastructure and human activities
Urban heat resilience planning matrix	Okvir za planiranje otpornosti gradova na vrućine	Matrix created for the purpose of planning a range of activities aimed at achieving urban resilience to UHI effects through heat reduction and control strategies

URBAN HEAT ISLANDS

URBAN HEAT ISLANDS

BACKGROUND INFORMATION

UHI is a microclimatic phenomenon, which occurs in urban environments and manifests itself in the elevation of temperatures in urban built-up areas in comparison to the surrounding undeveloped, i.e. green areas. Understanding the impact and pronounced effects of UHIs can be of use in detecting areas with a particular impact of economic activity, energy consumption, health factors, ecosystems, etc.[1]

City dwellers are exposed to higher air temperatures than rural residents due to UHI effects, which by default encompass a difference in air temperature between urban areas and their rural surroundings. In terms of number of days, the duration of heatwaves in European cities is two times longer than in the rural areas surrounding them.[2] UHIs are caused by factors limiting evaporative cooling, such as the high thermal capacity of cities, anthropogenic heat sources and impermeable surfaces.[3] Within European cities, UHIs cause large variations in temperature (e.g. during heatwaves, night-time temperatures in central Paris vary by 9 °C)[4] and their effects intensify in hot periods.[5]

Given their origin, UHIs are a microclimatic phenomenon characterised by elevated areal temperatures, which can be reduced by adequate planning and the inclusion of green infrastructure in urban space. At the moment, approximately 40% of European urban surfaces are green surfaces, with an average of 18.2 m^2 of publicly accessible green spaces per capita. In addition, only 44 % of the European urban population lives within walking distance (300 m) of urban parks.[6]

Anthropogenic modifications of natural spaces within urbanized areas have led to changes in weather conditions that are monitored within the frames of UHI impact research. The negative effects of UHIs have been observed in all urban areas, but particularly in bigger ones. By monitoring these changes, it is possible to identify and link the main impacts on UHIs on the basis of which the most effective measures for the mitigation of negative effects can be recommended.

---

[1] Mesarić et al., 2019
[2] Hooyberghs et al., 2017; Wouters et al., 2017
[3] Lauwaet et al., 2016
[4] Tzavali et al., 2015
[5] Dodman et al., 2022
[6] Maes et al., 2019

SITUATION IN CROATIA

Croatia is both a Central European country and a Mediterranean country whose climate is significantly influenced by its position in the temperate latitudes of the northern hemisphere. The most important regional climate factors in Croatia are the Mediterranean Sea, the Dinaric relief and the Pannonian Basin, in accordance with which Croatia is divided into three main climate areas: continental, mountainous, and coastal[7] (Figure 1).

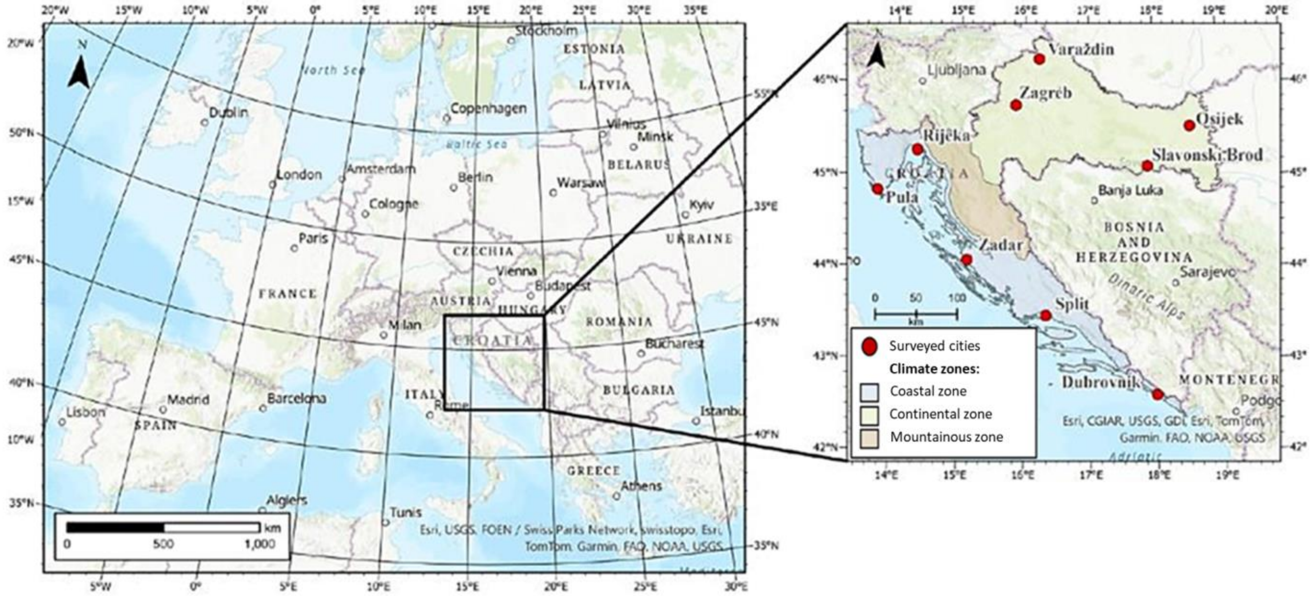


Figure 1 Climate zones of the Republic of Croatia (adapted from Žgela et al., 2024)

Zagreb is the largest urban area in Croatia, with a metropolitan area populated by approximately million residents. It is followed by Split and Rijeka, the only remaining cities in the country with more than one hundred thousand inhabitants. The majority of other urban areas in Croatia are small in comparison to European standards. During the summer, many coastal cities in Croatia become popular tourist hotspots, leading to an increase in the number of people at risk of heat hazards. This is indicated by the high average air temperatures during the Summer, along with less precipitation in comparison to continental cities. Additionally, the Mediterranean has been identified as one of the world's climate hotspots, meaning it is extremely exposed to the negative effects of climate change, combined with the effects of UHIs. This is an additional reason to plan the mitigation of these effects with the purpose of reaching a milder climatic future.

The impacts of UHIs are often discussed only in the context of million cities. However, UHIs may occur in smaller cities, as well, given that they are primarily a result of the concentration of artificial materials such as concrete, asphalt, glass, etc. Thus, it must be emphasised that UHIs may also appear in smaller urban areas, which are a frequent occurrence in Croatia. This may negatively affect the health of a great portion of Croatian resident. However, larger cities suffer a greater amount of more intensive UHI effects, as the difference between the temperature in the city centre and the surrounding area of major cities is more pronounced than in smaller cities.

Furthermore, certain cities are characterised by a significantly different urban morphology, greatly influenced by physical and geographical modifiers. For example, coastal cities are often more densely populated than continental cities, partly due to geographical reasons, and partly as a result of economic and financial reasons that cause littoralisation, which is why they tend to spread over narrow coastal zones. A large number of coastal towns in the hinterland of Croatia are limited by a mountain barrier that does not allow expansion into the continent, with littoralisation keeping a strong connection between the majority of the population and the coastal zone. As a consequence, coastal towns in Croatia have significantly more heterogeneous urban morphology than continental towns, which are commonly characterised by a simpler topography and are often located in river plains. The urban structure of towns in the Croatian interior is therefore more proper, as the expansion of the city

[7] Zaninović et al., 2008

could have been somewhat planned. Furthermore, riverside towns are characterised by a cooling effect, caused by the proximity of a water body which reduces the heat load.

The planning and implementation of heat load mitigation measures in different towns requires a well-thought-out approach that takes into account their geographical, climate and urban specificities.

The negative impact of UHIs on the city population and visitors is particularly pronounced in major Croatian cities and tourist destinations during the summer season. The intensification of negative UHI effects due to climate change is much more pronounced in the Mediterranean coastal area than in the mountainous and continental Croatia. In addition to different weather patterns, the given regions display differences with regard to the relief, urban morphology, and the materials traditionally used for construction, all of which contributes to an increase or a decrease with regard to the intensity of negative UHI effects. It is, thus, crucial to recognise all positive and negative elements and adapt measures for the mitigation of the negative effects of UHIs.

CLIMATE FACTORS INFLUENCING THE EFFECTS OF URBAN HEAT ISLANDS

Climate factors, such as air temperature, relative humidity, wind and precipitation play a key role in the emergence, development and intensity of UHIs. Elevated air and surface temperatures in urban areas come as a result of anthropogenic activities such as traffic, industry and heating. Furthermore, the impact of UHIs can be additionally enhanced by low relative humidity in cities due to drier soil and less impermeable surfaces, which are more prone to heating[8]. Slower air flows in cities make heat dispersion more difficult, and changes in humidity levels can increase residents' thermal stress.[9] During heatwaves, the effects of UHIs intensify and their scope varies from location to location and depending on the time of day.[10]

In the future, the dangers of heatwaves for cities and infrastructure can only increase.[11] By 2100, depending on the representative concentration pathways (RCP), as a result of the intertwined effects of heat and humidity, between half (RCP 2.6) and three-quarters (RCP 8.5) of the human population could be exposed to periods of life-threatening climate conditions.[12] According to all RCP projections by 2050, cities in medium latitudes will potentially be exposed to a heat stress level which is two times more intense than heat stress in their rural environments.[13]

In the Europe-focused chapter of the sixth report of the Intergovernmental Panel on Climate Change (IPCC)[14], it is stated that the risk of heat stress, including mortality and discomfort, depends on the level of socio-economic development. According to the same source, mortality and illness rates associated with elevated temperatures will be the highest in Southeastern Europe.[15]

Climate changes are already making a significant impact on UHIs, and, in the coming decades, higher air temperatures and changed weather patterns will only exacerbate the problem. The complex impact of climate change on UHIs involves numerous interactions between meteorological, ecological and urban factors.[16]

AIR TEMPERATURE INCREASE

In the past few decades, average temperatures in European urban areas have already increased by approximately 1–3 °C. Climate changes are caused by elevated average temperatures throughout the seasons. This leads to a greater thermal load in cities (Figure 2) due to an increased amount of heat being transferred to urban surfaces, such as asphalt, concrete, and roofs.

MORE FREQUENT AND INTENSE HEAT WAVES

In Central and Southern Europe, the number of days with extremely high maximum air temperatures (above 35°C) has increased, contributing to more frequent and intense heat waves that occur as early as in June and are possible even in September. In addition, they no longer last a few days, but rather a week or longer, and their intensity increases both during the day and during the night. Heatwaves caused by climate change further contribute to greater temperature differences between cities and their surroundings, emphasising UHI effects, which can have serious consequences for urban residents.

[8] Dodman et al., 2022
[9] Arnfield, 2003
[10] Dodman et al., 2022.
[11] Dodman et al., 2022; Leal Filho et al., 2021; Arias et al., 2021
[12] Dodman et al., 2022; Mora et al., 2017; Zhao et al., 2021
[13] Wouters et al., 2017
[14] Bednar-Friedl et al., 2022
[15] Bednar-Friedl et al., 2022
[16] Žiberna et al., 2021

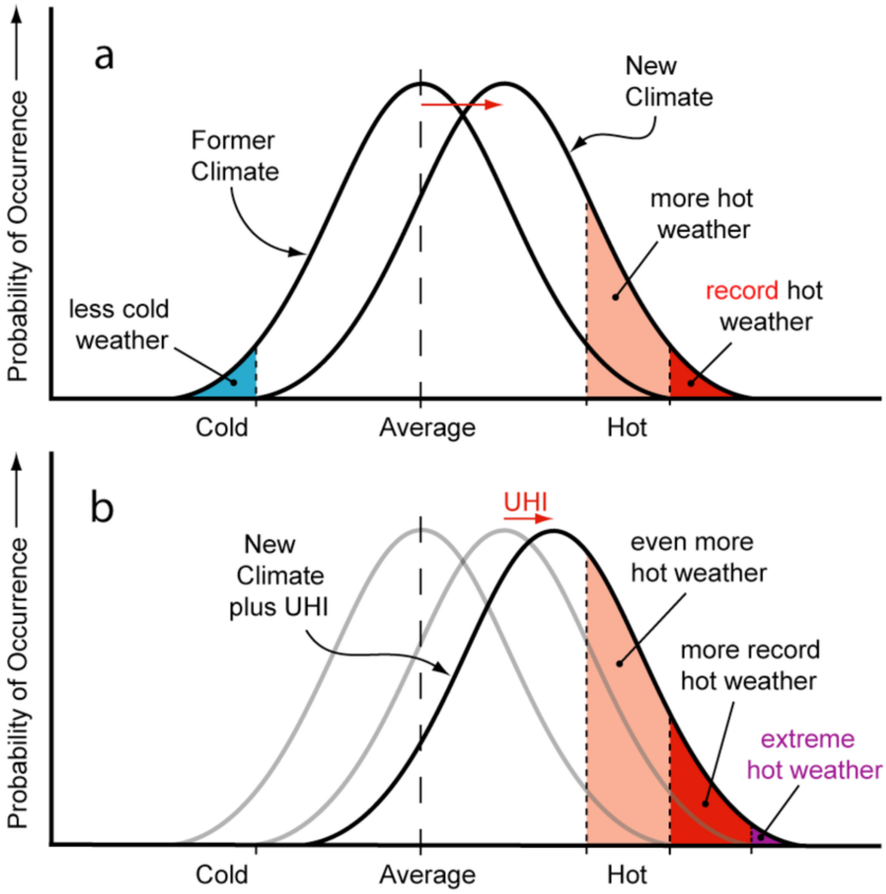


Figure 2 The combined effect of climate change (a) and UHIs (b) leads to additional temperature increases in cities[17].

CHANGES IN PRECIPITATION PATTERNS

Climate change also leads to changes in precipitation patterns, which can affect water availability in urban areas. Longer dry periods during the summer further enhance UHIs' effects, as green areas, such as grasslands and parks, are affected by physiological stress. Lack of precipitation can also limit cooling options and affect the water supply of the urban population.

Climate change can indirectly affect certain plant species by enhancing the reproduction of cohabiting organisms and stimulating the emergence of diseases that decrease the quantity and quality of green cover in cities, resulting in reduced urban shade and cooling capacities. Climate change also carries an increased risk of natural disasters, such as fires.

PROJECTIONS OF CLIMATE CHANGE IMPACT ON THE EMERGENCE OF UHIs IN CROATIA

Analyses conducted by the Croatian Meteorological and Hydrological Service clearly point to the UHI issue caused by climate change. Temperature increase in Croatia has been recorded in all temperature extremes indices. There is a significant rise in the number of warm days in spring and summer, as well as warm summer nights, in the Adriatic region. Temperature changes in continental Croatia are characterised by enhanced temperature increases in the Zagreb City area, which indicates a strong warming effect.[18] A particularly steep increase has been observed in the number of warm nights as a result of enhanced heating of concrete surfaces.

Compared to the period between 1981 and 2010, a minimum of 12 warm days more is expected to be measured every year in the whole of Croatia in the period from 2041 to 2070. The easternmost part of the country is expected to experience 12-15 warm days more, whereas central Croatia is predicted to record additional 15-18 warm days. Mountainous Croatia, as well as the interior parts of Dalmatia and Istria, will have up to 21 warm days more, and the narrow coastal area is expected to have up to 24 warm days more in the period between 2041 and 2070 in comparison to the period between 1981. and 2010. The summer season is the greatest contributor to the annual increase in the number of warm days. Interestingly, the largest spring increase (2-5 days) can be expected

[17] Brown, Helen et al, 2018
[18] Nimac et al., 2021

in the areas in which the increase in the number of warm summer days is the least pronounced compared to 1981-2010 (in certain parts of Central and Eastern Croatia and in Dalmatia). The largest increase in the number of warm days in the autumn season (between 5 and 7.5 additional warm days) is expected in the coastal Adriatic region, with the number of additional warm days decreasing as the proximity to the interior reduces.

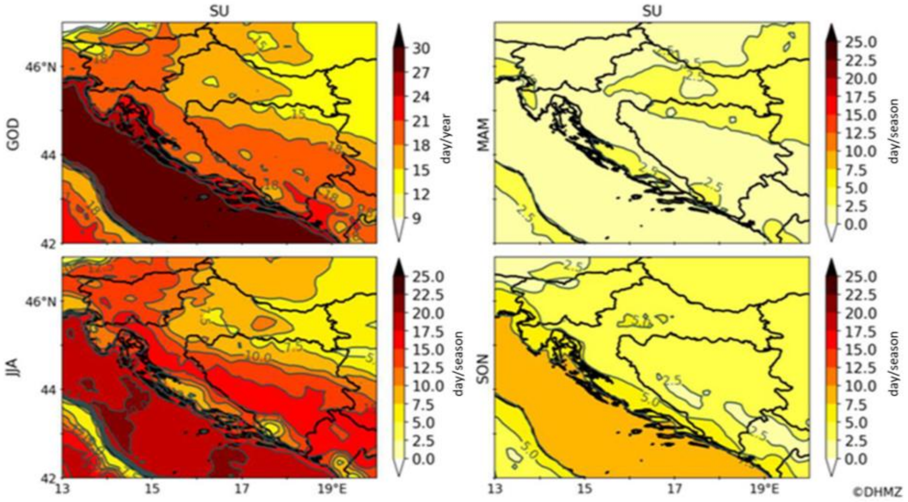


Figure 3 The change in the number of warm days between 2041 and 2070 compared to the period between 1981 and 2010 under the RCP 4.5 scenario. Annual change (GOD; top left), spring change (MAM; top right), summer change (JJA; bottom left) and autumn change (SON; bottom right)

Annual changes during warm periods (the number of days in periods with at least 6.0 consecutive days with a maximum air temperature surpassing 25°C, displayed in Figure 3) are consistent with the change in the number of hot days. The length of these periods gradually increases, starting from the east of Croatia (increase of 17.5–20 days), through the central and mountainous Croatia (increase of 20–32.5 days), reaching a maximum in the coastal region (increase of 50 days). This increase from eastern regions to coastal areas characterises all four seasons, but is the most pronounced in summer, and the least pronounced in winter. Spring and autumn warm periods will experience the longest extension in the coastal area, with 10 or more additional warm days in both seasons.

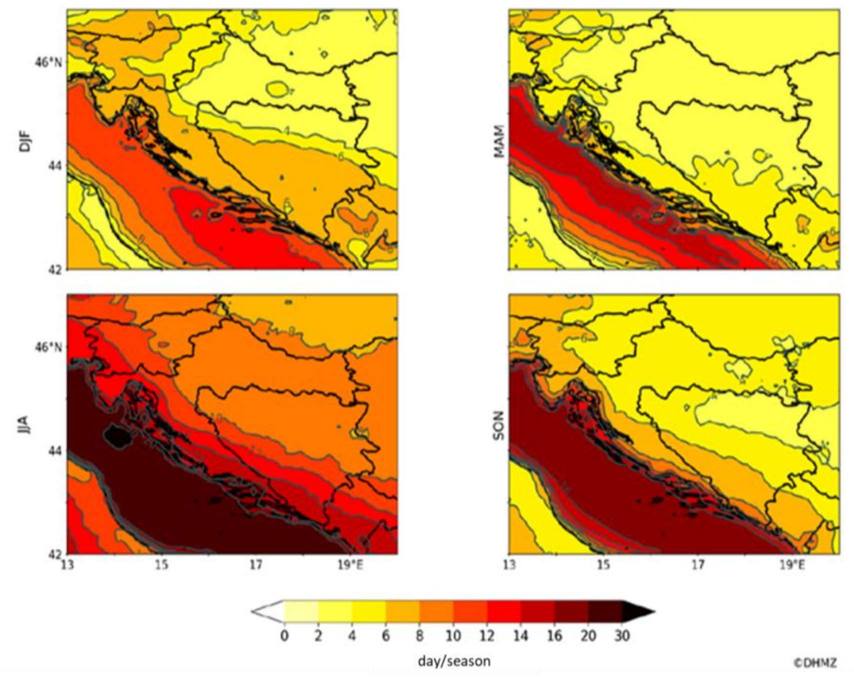


Figure 4 Change in the duration of warm periods in the period between 2041 and 2070 compared to the period between 1981 2010 for scenario RCP 4.5. Winter change (DJF; top left), spring change (MAM; top right), summer change (JJA; bottom left) and autumn change (SON; bottom right)

To identify UHIs, scientists use direct and indirect methods, numerical modelling and estimates based on empirical models. Remote sensing is often used to estimate surface temperatures. Based on the data collected, thermographic images, such as those in Figure 4, are produced.

Agapito et al. conducted an analysis of the expected heat load in the 21st century in Dubrovnik, Osijek, Rijeka, Zadar and Zagreb.[19] A significant increase has been observed with regard to average, maximum and minimum temperatures across all combinations of regional and global climate models in all cities analysed. In warmer climatic conditions, the number of days with a maximum air temperature surpassing 25°C increases in all cities analysed (especially in Dubrovnik), and so does the number of days with a minimal air temperature surpassing 20°C (especially in Rijeka and Zadar)[18]. The number of days with maximum air temperature in Dubrovnik surpassing 25 C (summer days – SU) and the number of days with a minimum daily air temperature surpassing 20°C (tropical nights – TR) are shown in Figure 5.

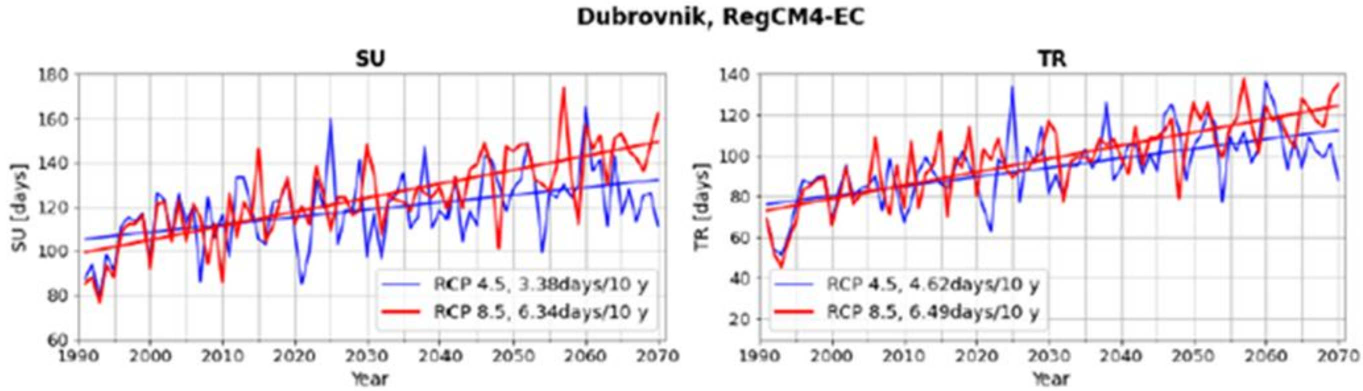


Figure5 Temporal series of climate indices of summer days (SU) and tropical nights (TR) for the RCP 4.5 (blue) and RCP 8.5 (red) scenario. The results for the city of Dubrovnik presented have been calculated on the basis of a combination of regional (RCM DHMZ-RegCM4) and global climate models (GCM EC). Trends with/without a statistical significance of 95 % are marked with a full or intermittent line. Summarised on the basis of: Agapito et al., 2023.

Climate factors contributing the most to negative UHI effects are rising temperatures, longer hot periods and changes in precipitation patterns, which further negatively affect the heat sensation and heat stress of the urban population.

[19] Agapito et al., 2023

IMPACT OF SPATIAL PLANNING AND CONSTRUCTION ON THE EFFECTS OF URBAN HEAT ISLANDS

In terms of urban revitalisation, the international scientific community sees climate change as a major challenge for global development and sustainability in the 21st century.[20] There are two main aspects of this challenge: (I) difficulties with regard to reaching an agreement on greenhouse gas emission reductions in international negotiations and (II) the need for urgent development of climate change adaptation strategies at national, regional and local levels.[21]

Climate forecasts for the future stem from different scenarios based on greenhouse gas emissions, which depend on population growth, consumer behaviour patterns, economy and politics.[22] The highest temperature increases during heatwaves are expected in Central Europe, and cities such as Ljubljana, Prague and Zagreb are expected to face significantly more frequent heatwaves.[23] Given that any prediction regarding future climate is highly uncertain, these predictions should not be seen as a forecast, but as a possible climate scenario.[24]

There are studies suggesting that socially and economically vulnerable members of society are more likely to inhabit warmer parts of cities, which are usually associated with a higher population density and higher construction rates. According to the results of these studies, these city parts consist of less thermally insulated housing units built from older materials of lower quality.[25] Reduced thermal comfort and increased risk of overheating to a large extent depend on the technical characteristics of buildings. These characteristics include thermal resistance, shading ability, heat mass, ventilation systems, as well as building orientation and its geographical location.

Urban areas in Europe where the health impacts of heatwaves are exacerbated by unfavourable microclimatic conditions in buildings, negative impacts of infrastructure, ATT and air pollution in 74% of the population.[26]

From a perspective of climate change adaptation, a city that has been adequately planned and designed is characterised by the following features[27] (Figure 6):

- its resources (space, energy, materials, water, etc.) are used efficiently with the purpose of minimising the city's global and regional environmental impact (e.g. particulate pollutant emissions and greenhouse gases, water pollution, waste generation)
- its parts are planned and constructed so as to improve the microclimate around buildings and their surroundings (or at least to block the deterioration of this microclimate);
- people and infrastructure in it are protected from extreme weather events, with current and future climate variability and extremes being taken into account.

[20] UNDP 2005, 2010; OECD 2009; World Bank 2012; UN-Habitat 2011a, b, 2014
[21] Musco and Magni, 2014
[22] IPCC 2007, 2012
[23] Guerreiro et al., 2018
[24] Brandenburg et al., 2018
[25] Dodman et al., 2022; Oke et al., 2017; Chow et al., 2014; Susca and Pomponi, 2020
[26] Smid et al., 2019
[27] Oke et al., 2017

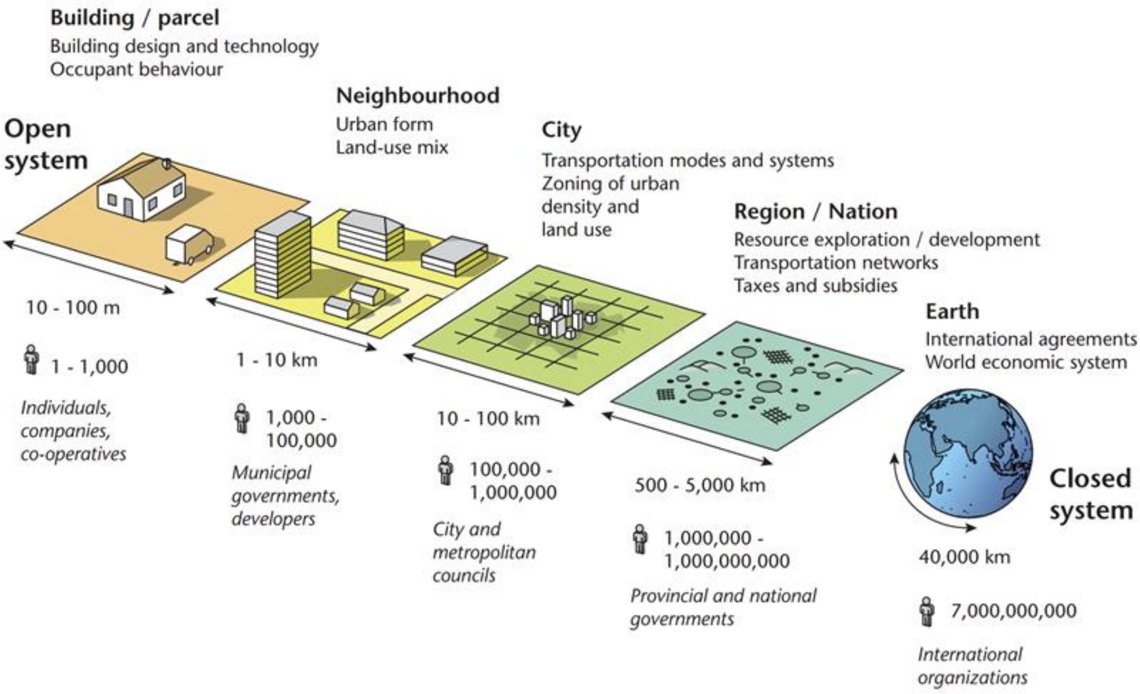


Figure 6 Hierarchy of decision-making on changes in urbanised landscapes (adapted in accordance with: Oke et al., 2017)

In addition to natural disasters, sustainability, mitigation, adaptation, renewable energy, the transition to a low-carbon economy, ecosystem planning and recovery planning are some of the new key concepts in spatial planning and governance discussions.[28] During the last couple of years, there has been an increase in the number of natural disasters, and planning is increasingly focused on building resilience, especially to UHIs. This falls within the scope of a fast-developing practice, and the urban planning profession is in a good position to take the leading role in this regard.[29]

Developing plans to make cities resilient to UHIs encompasses seven holistic and practical steps:[30]

1. setting clear planning targets, focused on preventing urban warming, and associated success measures
2. building a comprehensive heat risk database
3. developing a range of heat mitigation and control strategies
4. Managing risks
5. coordinating urban planning activities
6. involving other actors in planning processes
7. conducting effective implementation, monitoring and evaluation.

By summarising strategies for the management of thermal effects and processes, as well as documents and activities for practical application, it is possible to create a Heat Resistance Planning Framework illustrated by Matrix 1 (hereinafter: the Framework).[31] The Framework requires adaptation to local processes and serves as a tool for the process of making planning decisions and for project design, as well as a basis for discussing possible activities at different governance levels. Such a framework is potentially useful to all stakeholders in the implementation process.

[28] Musco et al., 2016
[29] Ladd, Meerow and Wagner, 2020
[30] Meerow and Woodruff, 2019
[31] Ladd and Meerow, 2022

	Heat reduction strategies					Heat control strategies				
	Land use	Climate-conscious urban design	Green infrastructure	Blue infrastructure	White infrastructure	Energy	Waste	Human exposure	Public health	Emergency services
Community engagement, vision and needs										
Engagement, vision, opportunities and priorities of the local government										
SPATIAL AND STRATEGIC PLANNING										
Spatial Development Strategy of the Republic of Croatia (OG 106/2017)										
Urban Green Infrastructure Development Programme 2021–2030										
Circular management of space and buildings development programme for the period 2021–2030										
Spatial plans for the development of cities and municipalities										
General urban plans										
Urban development plans										
Green Urban Renewal Strategies										
Climate change adaptation strategy in the Republic of Croatia for the period up to 2040 with a view to 2070										
Sustainable Energy and Climate Action Plan (SECAP)										
National Strategy for Disaster Risk Reduction 2030										
Strategic Planning Acts of National, Local and Regional Self-Government Importance										
LEGAL FRAMEWORK										
Construction Act (OG 153/13, 20/17, 39/19, 125/19)										
Physical Planning Act (OG 153/13, 65/17, 114/18, 39/19, 98/19, 67/23)										
Energy Efficiency Act (OG 127/14, 116/18, 25/20, 32/21, 41/21)										
PUBLIC INVESTMENT										
Green and blue infrastructure										
Other open surfaces										
Transport infrastructure										
Risk and disaster management infrastructure										
Public buildings										

Matrix 1 Framework for planning urban resilience to UHI effects adapted to specific national needs and sources (Ladd, Meerow, 2022)

The Spatial Development Strategy of the Republic of Croatia (OG 106/2017) emphasises the need to strengthen natural capital through the development of green infrastructure and to make the areas most exposed to UHI effects a priority for the introduction of such infrastructure. Two national programmes relevant to the UHI topic are:

- The Urban Green Infrastructure Development Programme 2021-2030 (GI Development Programme); and
- Circular Management of Space and Buildings Development Programme for the Period 2021–2030 (CM Development Programme).

The GI Development Programme lists temperature reduction and the mitigation of UHI effects as one of the environmental benefits of green infrastructure, and the infrastructure's economic benefit consists of reduced heating and cooling costs in residential and commercial premises. In terms of benefits to society, green infrastructure can alleviate the health problems associated with heatwaves and improve life in cities in general. These benefits resulted in the creation of specific objective 1: improved, expanded, connected and easily accessible green infrastructure in cities that solves various problems, including the emergence of UHIs. In view of the proven connection between UHIs and how built-up an area is, it is necessary to consider the reduction of the construction rate, i.e. the possibility of renovation and regeneration of unused or underutilized existing spaces and buildings, during spatial planning and construction. The CM Development Programme led to the creation of specific objective 2: circular renovation of unused spaces and buildings that includes abandoned individual buildings and monofunctional and polyfunctional zones of abandoned spaces.

At the moment, the whole Croatian system of spatial planning is undergoing transformation, especially as regards the digitalisation of the system of spatial planning, construction and state property, including the development of next generation spatial plans. For this reason, the Regulations on Spatial Plans (OG 152/2023) were adopted. Since the transformation process is still underway, it is not possible to predict the impact of the new system on UHIs. However, with the new Regulations in place, the possibility to define and designate the area in the green infrastructure system as an Area of Special Limitations has been enabled. For the purpose of ensuring efficient and focused green infrastructure planning processes, local self-government units will be given the ability to use the Green Infrastructure Registry. The Registry will contain a descriptive list and a map of the current state of green and other open public spaces in accordance with the typology of the Green Infrastructure Development Methodology.[32]

[32] Ministry of Physical Planning, Construction and State Assets, 2023

CLIMATE-CONSCIOUS URBAN DESIGN

Climate-conscious urban design is based on the application of nature-inspired solutions. Throughout history, numerous approaches and measures have been known to enable the coexistence of man and nature in the most adapted and least destructive way. Literature has helped popularise the concept of bioclimatic construction of cities and houses with the use of a number of available measures, applying the name “Design with climate” to the concept.[33]

Green spaces in urban environments have the ability to absorb toxic pollutants, thus contributing to air purification and ecosystem conservation. Additionally, they can improve microclimatic conditions and help address the ecological challenges of urbanisation and construction.[34]

Creating city parks and other green spaces is one way to create conditions for a pleasant stay in urban spaces. Climate-conscious urban design extends such an approach to the whole city.[35] When designed and executed well, such space design should enable the urban population to stay outdoors longer by implementing the following measures[36]: (ibid.)

• using materials and shaping process that are resilient and sustainable (planting deciduous tree species, utilizing smart materials, canopies, and water sprayers, taking into account insolation factors)

• implementing shaping processes which are adapted to local conditions (shaping processes that take into account the diversity of microclimatic conditions within city districts to provide residents with more opportunities to be outdoors in different weather conditions and seasons; for example, created microclimatic zones can provide shelter from wind, sun or precipitation).

Furthermore, during periods of highest traffic intensity, it is necessary to act with a focus on reducing emissions of harmful particulate matter and greenhouse gases from traffic, thermal energy of fossil-fuelled motorised vehicles, as well as the presence of cars in spaces exposed to direct solar radiation. At the same time, or even before such measures are introduced (starting from the city centre), sustainable urban mobility should be promoted. From the outset, efforts should be invested into creating efficient and easily accessible public transport, an accessible network of city bicycles, good cycling infrastructure and a fossil-free vehicle sharing system. Additionally, pedestrians need to be protected from the sun.

The scientific community has worked hard on defining potential strategies for climate change mitigation, but these strategies often cannot be applied in cultural and historical units and within the frames of individual cultural goods due to numerous limitations in heritage conservation,[37] e.g. architectural or urban modifications are often not allowed. Nowadays, reusing historical buildings is a common practice, but applying active or passive solutions for the purpose of interior design improvement is not always feasible due to architectural constraints.[38]

For architectural heritage and UHI mitigation measures to be successfully conducted, a dialogue and certain modifications are required, but the potential for developing such solutions is high. Cultural and natural heritage are key elements of sustainable and resilient urban communities because they create common values and connect people with the past and with nature. It is necessary to take a step forward and explore opportunities to integrate green initiatives into the practice of preserving and managing cultural heritage, both in the context of individual cultural assets and cultural landscapes.

For the process of planning measures focused on the mitigation of negative UHI effects to be successful, coordination between different levels, i.e. the national level and local self-government units, as well as the engagement of community stakeholders are required. UHI mitigation activities will involve the employment of experts in planning, architecture, construction, landscape architecture, forestry, climatology, energy and other fields; administrative departments of local self-government units for urban planning, physical planning, construction, communal infrastructure, transport, environmental protection, etc.; non-profit organisations

---

[33] Victor Olgyay, 1963
[34] Zellweger et al., 2020
[35] Oke et al., 2017
[36] Ibid
[37] Castaldo et al., 2017
[38] Leijonhufvud and Henning, 2014

focused on nature-inspired solutions and environmental issues, as well as private investors. Heat control activities require coordination between public health and emergency management departments, emergency services, energy distributors and local community organisations. The knowledge a local community possesses can be useful in planning UHI prevention measures, as it might provide a new perspective, new ideas and insights on risk sharing[39], so close cooperation with planners is desirable. Such a cooperation can enhance community members' awareness of UHI resilience measures and bring more balance to local circumstances connected to microclimate, resources and materials. The approach to architectural heritage should be based on innovative reinterpretation of the reasons that have "naturally" encouraged construction for centuries.[40]

Many authors have already recognised the great impact urban planning and design have on exposure to UHI effects. Considering the expected increase in the city's population, emphasis in spatial planning should be placed on the introduction of good practices and innovative measures focused on the mitigation of negative UHI effects. There are direct connections and consequences between spatial planning, construction practice and UHIs. Spatial plans and regulations and building standards must include measures focused on the mitigation and prevention of the negative effects of UHIs, both in buildings and in the built-up urban environment. Scientific insights with regard to UHIs must be included in the urban space planning and construction phases, whereas the extremely complex relationships between different influences that require a multidisciplinary approach and cooperation with different experts and representatives of the public should also be kept in mind.

[39] Corburn, 2003
[40] Musco et al., 2016

IMPACT OF URBAN HEAT ISLANDS ON THE ENVIRONMENT, RESIDENTS' HEALTH STATUS, AND SOCIO-ECONOMIC CIRCUMSTANCES

Impacts of UHIs on the environment and the health status of residents represents an important challenge in urban areas around the world. Rapid urbanisation has led to an increasing number of UHIs in areas where urban temperatures are significantly higher than in extra-urban areas. As the temperature rises and cities expand, the intensity and severity of UHIs is increasing.[41] This can lead to a number of adverse consequences, ranging from changes in ecosystems, to increased energy consumption due to greater cooling needs, all the way to various health problems among the residents. Elevated UHI temperatures can cause various health problems, including heat strokes, dehydration, respiratory diseases, as well as the exacerbation of chronic health conditions such as asthma and cardiovascular diseases.[42]

ELECTRICAL ENERGY CONSUMPTION

UHIs play a major role within the frames of energy consumption in buildings, as it causes increased use of air conditioners. In summer, total electricity consumption and peak energy load can rise by as much as 20%. With each additional degree by which air temperature rises in the 20–25°C temperature range, the demand for electricity for air conditioning or cooling increases by 3 to 4%. Cities may thus require 5–10% of electrical energy more to be able to control UHI effects. Energy consumption is usually the highest during hot summer weekday afternoons, when air conditioners, lighting and other appliances are used in offices and homes. During extreme heat which amplifies UHI effects, increased use of air conditioners can burden power systems or even lead to a disruption in electricity supply.

Research conducted in Modena, Italy[43] has shown that the use of new materials and technical solutions can lower surface roof temperatures by as much as 6°C, which also points to the possibility of saving cooling energy and reducing thermal pollution in urban spaces.

One of few positive effects of UHIs is the decrease in energy consumption for heating in dwellings during the cold period of the year. This is evidenced by a study conducted in Chinese cities,[44] which concludes that the decrease in the need for heating results not only in reduced coal consumption, but also in improved air quality and lower pollution levels in cities. The impacts of climate change and UHIs were also analysed in all three Croatian regions and[45] the correlation between energy consumption and climate change in the warmer and colder part of the year has been recorded.

INCREASED GREENHOUSE GAS AND PARTICULATE MATTER EMISSIONS

An increase in the electricity consumption caused by cooling needs leads to higher emissions of air pollutants and greenhouse gases, as fossil fuels still account for a large share of the energy mix. These pollutants have a detrimental effect on human health, as they exacerbate air quality by creating low ozone (smog), fine particulate matter and acid rains.

ENDANGERING THE HEALTH, PRODUCTIVITY AND COMFORT OF CITY DWELLERS' LIVES

Heat stress is linked to a number of health problems urban residents face, with its health effects unevenly distributed among the urban population. UHIs contribute to higher daily temperatures, reduced night cooling and higher air pollution, and these factors may contribute to heat-related deaths and health conditions associated with heat waves, such as general discomfort, respiratory problems, heat spasms, heat exhaustion and heat stroke. (Figure 7). The elderly display a particularly high vulnerability to heat due to physiological, psychological and socio-economic reasons. The elderly population, especially women, is often of poor health, is more vulnerable to high

[41] IPCC, 2023
[42] Santamouris, 2020
[43] Magli et al., 2015
[44] Ding et al., 2018
[45] Cvitan and Sokol-Jurković, 2016

temperatures, deals with poor mobility, is isolated and has lower incomes. Children also belong to the sensitive group due to their low body weight and other age-related factors. For example, the combination of their rapid breathing rhythm, prolonged outdoor stay and their developing respiratory system increases the risk of worsening asthma symptoms and other pulmonary diseases caused by poor air quality during heat waves. Lower-income populations are also at greater risk due to poor housing conditions, including a lack of air conditioning. During heatwaves, people with diabetes, physical impairments and cognitive impairments are particularly vulnerable.

There is clear evidence of increased health risks for older people in cities, in particular increased mortality rates during heatwaves as a result of UHIs.[46] Research conducted in European cities points to a correlation between the intensity of UHIs effects and an increased mortality rate,[47] which has been confirmed in studies[48] on mortality rates during heatwaves in Croatia. Compared to stabilisation at 2°C, the stabilisation of global warming at 1.5 C in major European cities would reduce the number of premature deaths during the summer months by 15-22 %.[49]

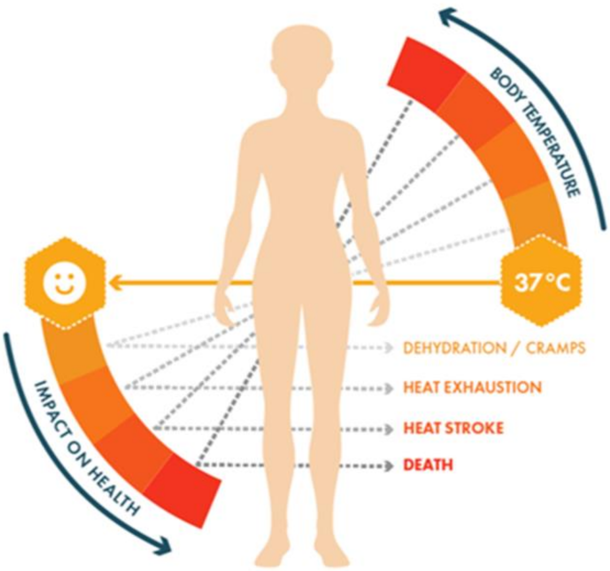


Figure 7 High air temperatures can seriously endanger human health, causing dehydration and heat exhaustion

Heat stress and dehydration are also associated with behavioural and learning problems, as dehydration interferes with concentration and cognitive functions in both adults and children.[50] According to the literature on the impact of heat on children, there is an increased need for urgent medical care due to heat-related diseases, electrolyte disturbances, fever, kidney diseases and respiratory diseases in young children.[51]

Studies on climatic factors that affect the incidence of epileptic seizures, apart from air pressure and other biometeorological factors,[52] have pointed to a number of negative events in the warmer part of the year.

The negative influence of temperature growth on the human body has been observed in Croatia-focused research as well[53], and during temperature increases, especially above 36 C, a more frequent incidence of neurovegetative symptoms has been discovered. In Croatian research on the interrelation between different types of climate change[54], it has been found that during heatwaves, in addition to a rise in population mortality rate, there has been a rise in the number of infectious diseases due to the impact on participants in the transmission cycle.

---

46 Arias et al., 2021
47 Huang et al., 2023
48 Zaninović and Matzarakis, 2014
49 Mitchell et al., 2018
50 Merhej, 2019
51 Winquist et al., 2016
52 Tomasović et al., 2022
53 Zeninović, 2003
54 Zeninović and Gajić-Čapka, 2008

Higher temperatures in urban areas also represent an economic burden for residents and households due to higher energy consumption during warm periods, but also due to medical costs associated with heat-induced conditions, increased absenteeism and other consequences.[55] There is a disproportion with regard to the increase in risk levels for people of lower socio-economic status exposed to urban heat. These risks are connected to inadequate housing conditions, more difficulties in access to air conditioners, work in intense occupations and waste collection in the open air.[56]

OTHER ENVIRONMENTAL ASPECTS: WATER QUANTITY AND QUALITY, FIRE RISK, HABITAT FRAGMENTATION, GREEN INFRASTRUCTURE

The emergence of UHIs affects not only air quality in the city, but also the urban water supply system. Due to higher temperatures, the stability of water reserves, biochemical cycles and biological activity change indirectly and directly. High temperatures on the surface of roads and roofs can heat up rainwater that drains into the drainage channels and consequently raise the temperature of the river, lake or sea into which it is discharged. Water temperature affects all aspects of freshwater and marine life, especially the metabolism and reproduction of many aquatic species. If there are not enough green infrastructural elements, such as rain gardens, permeable pavements, green parking lots and green roofs, in the city, there is also a lack of possibilities to cool rainwater during its run off.

UHIs negative effects, which will become even more severe due to climate change, will also have a major impact on urban demand and water consumption. Excessive consumption of water from nearby sources due to increased heat can burden water resources and lead to water scarcity in cities, which can in turn affect the water supply of a wider area.

UHIs are among the various factors contributing to fire risk in the city or its surroundings as they increase evaporation, drain the ground and lead to the drying of vegetation, which then helps fire to spread. Such fires are easily spread by wind from the outskirts to the centre of the city. UHIs also play a role in reducing biodiversity by further incentivising the loss and fragmentation of wildlife habitats.

Extreme heat is an additional aggravating factor in the organisation and maintenance of outdoor sports and cultural events, as it can have a negative impact on sports results,[57] but also on the viewers' perception and health.[58]

As urbanisation intensifies, UHIs' intensity is increased by factors such as the expansion of impermeable surfaces, reduction of the share of green infrastructure, and implementation of heat-producing activities. Average temperatures also affect the values of real estate, their utilisation and occupation rate and the general attractiveness of investments, and higher temperatures lead to a decrease in the value of real estate.[59] In addition to this, the discomfort and health risks associated with urban heat increase rent cancellations and reduce the attractiveness of housing.[60] This is why spatial planners, urban planners and similar experts are increasingly working on mitigating UHIs by designing green roofs, planting trees and installing cooling technologies to improve the quality of life and the value of real estate.[61] These activities not only contribute to climate resilience, but also strengthen the long-term sustainability and competitiveness of urban real estate markets.

In Croatia, the implementation of certain measures of the GI Development Programme aims, among other things, to raise the quality of green infrastructure standards and its accessibility, which will contribute to health and social inclusion of all population groups. One of these measures covers the renovation of existing infrastructure and the development of different types of green infrastructure, with an approach combining energy efficiency measures

---

[55] Jovanović et al., 2015; Liu et al., 2019; Schmeltz, Petkova and Gamble, 2016; Soebarto snd Bennetts, 2014; Zander and Mathew, 2019; Zander et al., 2015
[56] Chu and Michael, 2018; Santha et al., 2016
[57] Brocherie, Girard and Millet, 2015
[58] Aleksandria et al., 2018, Grundstein and Williams, 2018
[59] Oberoi et al., 2019
[60] Chakraborty et al., 2019
[61] Shi et al., 2020

and circular management of space and buildings.[62] The second set of the measures includes informing the population about the importance of green infrastructure in urban areas and its positive impact on all aspects of life – economic, social, environmental and cultural. Its aim is to raise the population's awareness of green infrastructure due to the importance of nature representation in everyday urban life.[61]

Studies focused on the impact of temperature increases on tree growth and development in European cities have shown that temperature increases stimulate earlier development of stages of the biological cycle (phenophasis).[63] It is important to note that urban space is viewed mosaically, so that the intensity of UHIs, which varies within cities as well, can be defined in detail.[64] In addition, the increase in temperature leads to the extension of the growing season of different species in warmer urban habitats compared to the same species in the surrounding rural areas with lower air temperatures.[65]

The negative impact of UHIs on urban green infrastructure is manifested in increased physiological stress, as well as in disruptions of plant physiological processes, which can decrease green infrastructure's efficiency with regard to reducing temperatures in the city. These processes reduce plants' expected life span,[66] especially when it comes to plant species that are not adapted to arid and warm conditions.

[62] Ministry of Physical Planning, Construction and State Assets, 2021
[63] Chmielewski and Rötzer, 2001, Holz et al., 2011
[64] Celina, 2019
[65] Zipper et al., 2016
[66] Roloff, 2013

IDENTIFICATION AND MAPPING

IDENTIFICATION AND MAPPING

BRIEF REVIEW OF SPECIALIST LITERATURE FOCUSING ON CASE STUDIES ON URBAN HEAT ISLAND IDENTIFICATION

Due to the major importance of climate change adaptation, a number of studies have been carried out on the intensity of UHI effects with regard to the type of land by purpose and cover[67], as well as in relation to the detailed land use categories defined in the Urban Atlas. One of the studies focused on measuring temperatures in the City of Karlsruhe, Germany.[68] Values which were measured there were compared with remote sensing data and characteristic land uses for all measurement areas.

The results of the abovementioned analysis are showcased in Figure 8,[69] where the authors calculated the average summer temperature at ground level in the period from 2001 to 2010 and for 30 different types of land use.

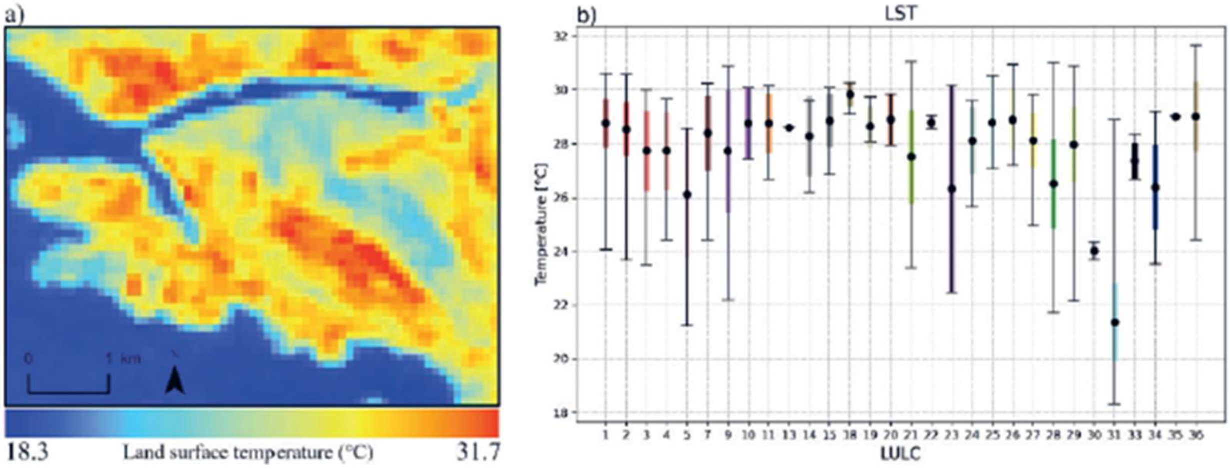


Figure 8 Average summer air temperature at the ground level for the city of Dubrovnik in the period from 2001 to 2010 based on LANDSAT5 satellite data (a) and an indication of the average soil temperature in relation to land categories (b). Summarised on the basis of: Boras et al. (2022).

Given the similarities in the context of climatic and geographical characteristics of certain areas of Croatia, the analysis of UHIs in Ljubljana,[70] which determined the soil temperature based on Landsat satellite images, should also be discussed. The results of the analysis indicated that UHIs emerge in spring, summer and autumn. It has also been established that the highest surface temperatures occur in industrial zones and commercial and business centres, especially in summer.

As for Croatia, a UHI analysis was made for the city of Zagreb based on the measurements of nine meteorological stations in the Croatian Meteorological and Hydrological Service (DHMZ) and Pljusak (amateur networks of automatic meteorological stations) networks in the period from 2013 to 2017[71]. Based on the analysis, the highest UHI intensity in Zagreb was recorded during the winter months, while the lowest was observed in the summer. The Zagreb Airport station stood out as the coldest station with an average annual temperature of 16.2°C, while Dugave and Zagreb-Grič stations stood out as the hottest stations with an annual average of 18.3°C and 17.9°C respectively (Table 1).[70]

[67] Mohan et al., 2003; Unger et al., 2001; Zou et al., 2021; Rendana et al., 2023
[68] Gangwisch et al., 2023
[69] Boras et al., 2022
[70] Cedilnik, 2015
[71] Žgela, 2018

Monitoring station	Winter (°C)	Summer (°C)	January (°C)	Mean annual temperature (°C)
Dugave	1,5	2,8	1,5	2,1
Gornje Vrapče	0,9	1,9	1,1	1,5
Retkove	0,8	0,9	0,9	1,0
Ferenščica	1,2	1,6	1,3	1,5
Mlinovi	1,5	0,1	2,0	1,1
Zagreb-Grič	2,0	1,2	2,1	1,7
Zagreb-Maksimir	0,6	0,0	0,6	0,4
Zagreb-Rim	1,0	0,1	1,0	0,7

Table 1 The intensity of UHIs according to data from monitoring stations in winter, summer and January, as well as their annual mean values for the period from 2013 to 2017. Summarised on the basis of: Žgela, 2018.

Figure 9 shows the results of UHI analysis prepared as part of the Climate Change Adaptation Plan of the City of Dubrovnik. This map combines building surfaces, impermeable surfaces and surface temperatures. Impermeable surfaces (percentage within the hexagon) and surface temperature (average value within the hexagon) constitute a sensitivity indicator, and the surface area of buildings within the hexagon represents the exposure value.[72]

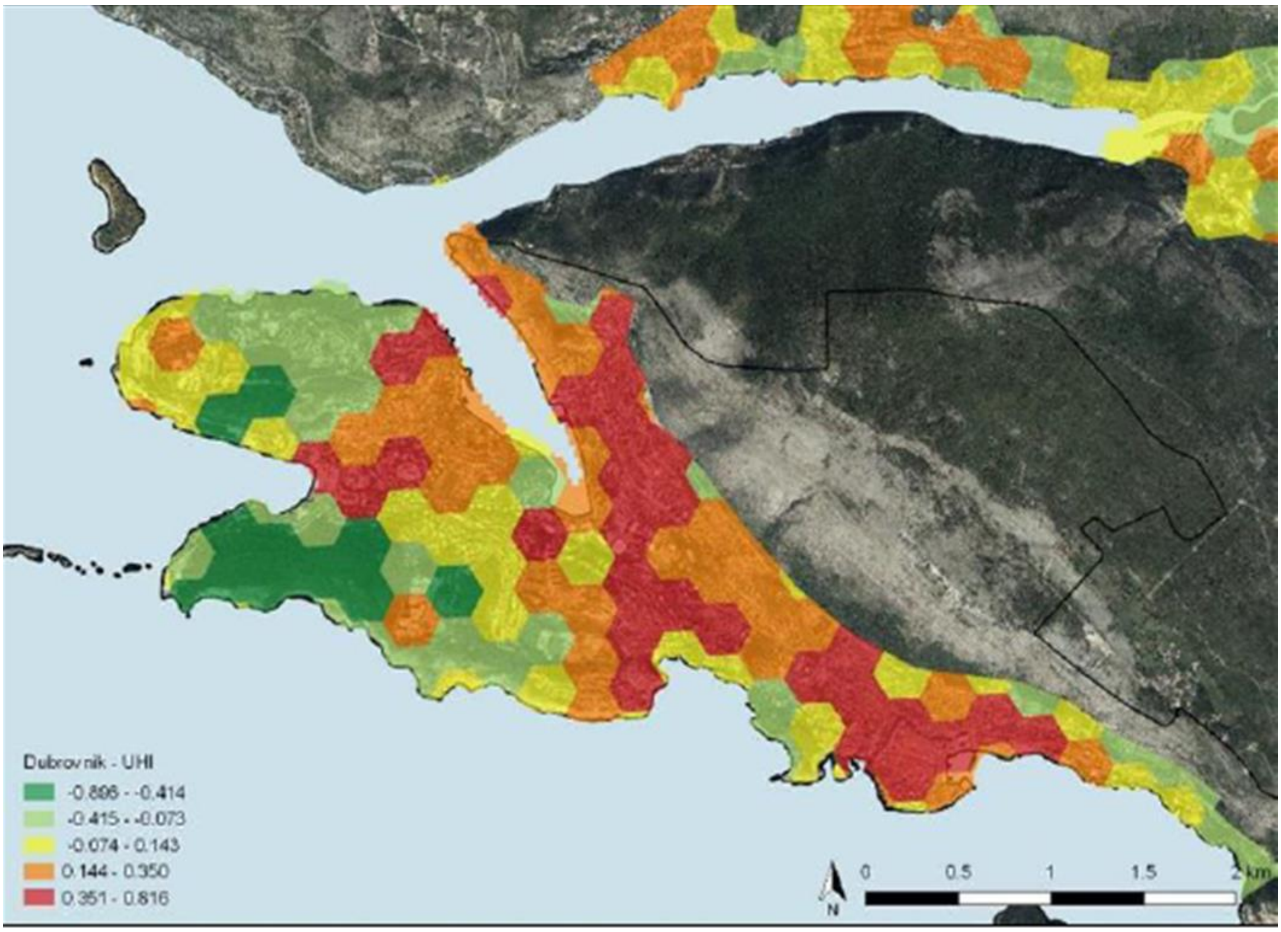


Figure 9 Map of sensitivity to urban heat islands in the city of Dubrovnik. Summarised in accordance with Mesarić et al., 2019.

Although a fraction of Croatia-based analyses have been partially carried out, they[73] lack an integrated approach. Žgela et al.[74] considered only a few individual points within the city, so their results are not suitable for mapping.

[72] Mesarić et al., 2019
[73] Boras et al., 2022; Mesarić et al., 2019; Seletković et al., 2023; Žgela et al., 2018
[74] Žgela et al., 2018

A good example of UHI analysis in Zagreb is the study by Seletković et al.[75], but they used remote sensing data only for certain days, not for a larger number of summer days for a given year. The analysis of results based on a one-day measurement cannot be considered as a representative sample. The climate change adaptation plan of the city of Dubrovnik is[76] also a good example of remote data sensing utilisation, but for the purposes of our methodology, there is no link with the types of land use. Likewise, the resolution of the hexagons shown in Figure 9[75] is equal to 160 m only. The most suitable results for the analysis would be the results published by Boras et al.[77], who calculated the average temperature of the soil surface in the field for different types of land according to the purpose in Dubrovnik. However, these data are not available in the form of a table but in the form of a graph (Figure 10), so their values cannot be derived with sufficient accuracy.

Seletković et al.[74] calculated the effect of UHIs in Zagreb using Landsat 8 remote sensing data for a day only in 2013, 2015, 2017, 2019, 2020 and 2022, i.e. throughout the six years. The UHI limit value was defined according to the following equation: $UHI > \mu + \sigma/2$, where μ and σ represent the average soil surface temperature of the Zagreb area and the standard deviation from that temperature.

The methodology used by Žiberna and Ivanjšič[78] for the city of Maribor is based on the surface temperature data produced by a Landsat satellite with a spatial resolution of 30 m, with the calculation of the average seasonal temperature of surfaces calculated by categories of the Urban Atlas. UHI intensity according to the abovementioned methodology is defined as the difference between the average temperature of a given land category in a given period, and the reference surface temperature in the same period, with the authors employing the average temperature of the ‘pastures’ category (one of land use categories according to the urban atlas: 2300) as the reference temperature.

The analyses for the city of Maribor were carried out from 12 April 2013 to 8 August 2020. During this period the land use in Maribor has not changed significantly. For the calculation of average seasonal surface temperatures (Table 2), meteorological seasons were taken into account. The results of that analysis showed that surface UHIs were the most pronounced in spring and summer. More specifically, the highest temperature differences in Maribor during this period were recorded in summer (6.6 C) and in spring (6.2 C). The autumn temperature differences amounted to an average of 4.3°C, and the least pronounced differences were observed in winter, with an average of 1.7°C. In summer, the most prominent temperature differences /in comparison to the temperature reference value of the pasture category) were recorded in the following categories: enclosed areas, densely built-up surfaces with impermeability levels surpassing 80% (4°C), industrial, commercial, public and military surfaces (3.7°C), as well as railways and related lands (3.3°C). Compared to the reference surface, lower temperatures were recorded in the following categories: water surfaces (lower by 2.6°C), forest surfaces (lower by 1.8°C) and independent buildings (lower by 0.2°C), where surrounding gardens and lawns help reduce temperatures (Table 2).

Given the differences in UHI intensity in large cities, which were calculated by Žgela et al., as well as Žiberna and Ivanjšič, as part of their research, it is necessary to emphasise the importance of research methodology and data collection. Improved data accuracy could be achieved by increasing the quantity of the results of the measured temperature on the unit surface. Therefore, the source of data from satellite imagery used by Žiberna and Ivanjšič is more robust, i.e. more usable than measurements by individual sparsely distributed sensors. It is also important to recognise the differences between the data obtained by measuring the temperatures at soil surface level, data obtained by measuring the temperatures at a height of 2 m above the ground, which is the standard height for air temperature measurements in meteorological stations, and data obtained by measuring the temperatures above the canopy. Thus, there are different forms of UHIs – surface islands (SUHI) and atmospheric islands (AUHI). The severity of UHIs can also be influenced by other factors, such as the density of buildings in tan area, as well as the building material used, especially in the identification methodology with a small number of measuring points.

[75] Seletković et al., 2023
[76] Mesarić et al., 2019
[77] Boras et al., 2022
[78] Žiberna and Ivanjšič, 2022

Land Use/Land Cover classes	Summer (°C)	Spring (°C)	Fall (°C)	Winter (°C)
Continuous Urban Fabric (S.L. >80 %)	21,1	29,1	22,0	3,7
Disontinuous Dense Urban Fabric (S.L. 50 - 80 %)	20,8	28,2	21,5	3,5
Discontinuous Medium Density Urban Fabric (S.L. 30 - 50 %)	19,9	27,1	21,0	3,4
Discontinuous Low Density Urban Fabric (S.L. 10 - 30 %)	18,9	25,7	20,1	3,4
Discontinuous Very Low Density Urban Fabric (S.L. <10 %)	18,7	25,5	20,0	3,4
Detached buildings	18,2	24,9	29,6	3,5
Industrial, commercial, public and military areas	21,2	28,8	22,1	3,7
Highways and associated areas	19,3	26,3	20,4	3,2
Roads and associated areas	20,0	27,3	21,0	3,4
Railroads and associated areas	20,9	28,4	21,9	3,6
Mines and dump sites	18,8	26,3	20,3	2,8
Land Without Current Use	19,9	27,0	20,9	3,4
Urban green areas	18,9	26,2	20,1	3,9
Sport and leisure facilities	19,2	26,3	20,3	3,0
Agricultural land	18,9	25,6	20,3	3,0
Orchards (Vineyards, Olive groves)	19,2	25,6	20,2	4,0
Pastures	18,5	25,1	19,8	3,6
Forests	16,0	23,3	18,2	2,3
Water surfaces	15,0	22,5	17,8	2,4
source: Landsat 8 TIRS [22], source autors own calculations, 2021.				

Table 2 Surface temperatures in Maribor by land use categories and by season. Summarised on the basis of: Žiberna and Ivanjšič, 2022. Note: no port area in accordance with the Urban Atlas.

Important analyses of UHI effects on different LULC (Land use/Land cover types) land use types is also represented in the work conducted by Boras[75] et al., as well as Žiberna[76] et al. As shown in Figure 10, Boras et al. estimated UHI impact using the remote sensing method by studying temperatures in different parts of the city during the summer and linking data that were observed in this period to land use data.[75]

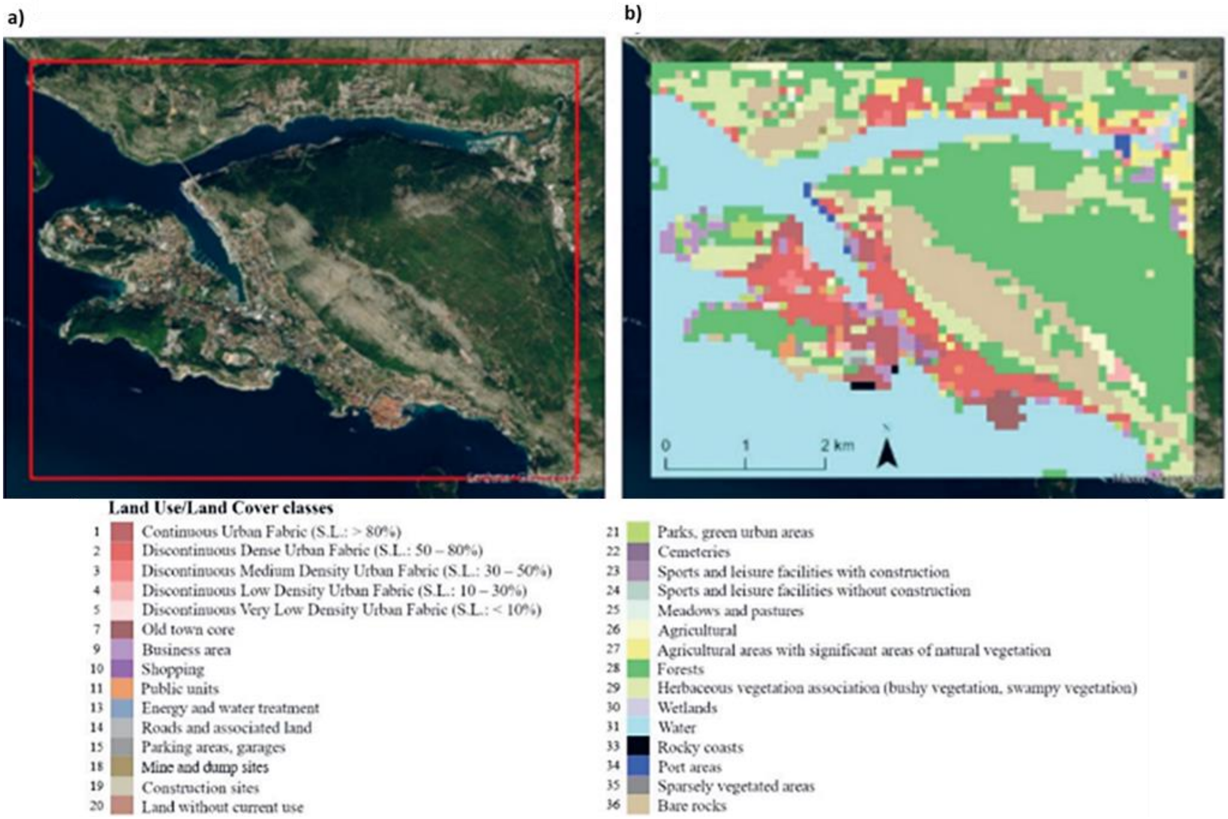


Figure 10 Satellite images of the area of the Dubrovnik City area and the land category according to the land classification by use and cover. Summarised by Boras et al., 2022.

As temperature data are not always available, using UHIs' intensity categories according to existing literature, indicating the link between the Urban Atlas land use categories and UHI intensity categories (e.g. Table 2) is recommended).

OVERVIEW OF METHODS OF URBAN HEAT ISLAND IDENTIFICATION

There are numerous methods and techniques in the literature that can be used to determine the scope and properties of UHIs, differing in terms of research aim, input data, precision and the level of complexity. The most commonly used methods are numerical modelling, remote sensing analysis and field measurements.

Numerical modelling

Microclimate modelling enables the simulation of cities' thermal characteristics, taking into account factors such as construction, green areas and urban matrix. Furthermore, such modelling allows the use of different temporal and spatial scales, as well as the administration of sensitivity tests. However, their results depend on the models' settings (resolution, parametrisation, small-scale physical processes, etc.) and therefore only roughly describe urban thermal characteristics.

Remote sensing

Remote sensing analysis largely depends on the thermal sensors found on satellites (example of sensor types in Table 3). These sensors measure surface temperatures which differ from the air temperatures measured by meteorological stations. Surface temperatures actually represent the temperature of the substrate. It differs with regard to the material and is most often lower in natural materials. The remote sensing technique allows data to be downloaded in different spatial and temporal resolutions and helps establish a spatial sample of surface UHIs (SUHIs). SUHIs depend on surfaces' thermal properties and are estimated by variations between surface temperatures (not air temperatures) of urban and rural areas. Surface temperature data are available from various sources, such as Landsat-8 and Sentinel-3 satellite imagery. The resolution of the Landsat-8 imagery is 30 m, and the resolution of Sentinel-3 imagery is equal to 20 m. Table 3 displays the characteristics of remote data collection device, and other data can be found via the link.[79] In addition, other data sources, such as MODIS[80] (characterise by low spatial, but high temporal resolution) and ECOSTRESS[81] (characterise by high spatial and temporal resolution) are available.

[79] Copernicus, CORINE: *https://land.copernicus.eu/en/products/corine-land-cover*
[80] MODIS: https://modis.gsfc.nasa.gov/data/dataprod/mod11.php
[81] ECOSTRESS: https://lpdaac.usgs.gov/products/eco2lstev001/

CHARACTERISTICS	CLC 1990	CLC 2000	CLC 2006	CLC 2012	CLC 2018
Satellite data	Landsat-5 MSS/TM, single date	Landsat-7 ETM, single date	SPOT-4/5 and IRS P6 LISS III, dual date	IRS P6 LISS III and RapidEye, dual date	Sentinel-2 and Landsat-8 for gap filling
Temporal extent	1986-1998	2000 +/- 1 year	2006+/- 1 year	2011-2012	2017-2018
Geometric accuracy, satellite data	≤ 50 m	≤ 25 m	≤ 25 m	≤ 25 m	≤ 10 m (Sentinel-2)
Min. Mapping Unit/Width	25 ha / 100 m	25 ha / 100 m	25 ha / 100 m	25 ha / 100 m	25 ha / 100 m
Geometric accuracy, CLC	100 m	better than 100 m	better than 100 m	better than 100 m	better than 100 m
Thematic accuracy, CLC	≥ 85% (probably not achieved)	≥ 85% (achieved)	≥ 85%	≥ 85% (probably achieved)	≥ 85%
Thematic accuracly, CHA	-	not checked	≥ 85% (achieved)	≥ 85%	≥ 85%

Table 3 Data on Corine land cover, a spatial sensor for data collection – extract

Field measurements

This method involves data from official weather stations or networks of temperature sensors across the city, as well as mobile measurements, conducted by e.g. cars or bicycles that measure air temperatures at different locations in the city. It is often used to analyse the lower layer of urban atmosphere (CUHI). CUHI refers to differences in air temperature of the lower layer of urban atmosphere and non-urban/rural areas. Standard spot measurements in meteorology offer continuous data for different parameters, but do not allow a detailed study of the spatial distribution of thermal load in the city due to the limited number of stations, resulting in data scarcity. For example, the Croatian Meteorological and Hydrological Service keeps data from only three stations in the City of Zagreb, which is useful for long-term UHI research, but not for a detailed understanding of the spatial distribution of heat in the city.

Other methods include:

- thermographic imaging with infrared cameras for temperature measuring at local level
- measurements taken by balloons or drones with the purpose of determining temperatures at different altitudes above urban areas
- surveys and other forms of social research that provide insight into the exposure of residents to high temperatures in urban areas.

PROPOSAL FOR A BASIC UHI IDENTIFICATION AND MAPPING METHODOLOGY

UHI identification is a process focused on identifying and quantifying temperature differences indicating UHI effects, and its main objective is to determine the presence and intensity of these effects. Mapping involves a visual representation of these effects on the basis of cartographic representations and a Geographic Information System (GIS).

Identification – UHI presence and intensity information

Mapping – facilitates spatial analysis and decision-making by visualising UHI samples and distribution

THEORETICAL FRAMEWORK

Solar radiation

Understanding the patterns of spatial distribution of sunlight is particularly important for a quality UHI analysis. For a better insight into the key aspects of the recommended methodology described in the upcoming chapters, the theoretical framework and the main terms connecting solar radiation and UHIs are presented below.

Human activity is the most important cause of UHIs, as it leads to their creation. However, their main natural driver is solar radiation, i.e. thermal energy reaching urban surfaces. Different locations within cities receive a different amount of sunlight, depending primarily on shading objects such as buildings and trees. A good illustration of this is the common habit of pedestrians to choose the shaded side of the street in times of great heat for movement.

It is the urban structure that influences the limitation or facilitation of exposure to the sun's rays. In many cities around the world, urban planning takes into account the orientation of buildings with the purpose of influencing the amount of solar energy that a building, i.e. some urban areas, receive during the day. This includes a set of rules and decisions aimed at maximising energy efficiency and reducing energy consumption.

To begin with, it is important to emphasise that the energy balance of the city depends on incoming and outgoing heat fluctuations, to whose source is solar radiation and longwave radiation from atmosphere. However, there are significant differences between the city and its rural surroundings precisely due to the large number of anthropogenic elements that alter this balance. This is clearly explained in Figure 11. All incoming solar energy is shortwave solar radiation. It heats up the surface and can be direct or diffuse. Diffuse radiation is scattered from particles in the atmosphere or from constructions on the Earth's surface. In cities, there are various other processes of energy movement that need to be kept in mind. First and foremost, there are urban surfaces reflecting less incoming energy compared to natural surfaces, which store more heat. Therefore, compared to rural areas, a higher percentage of heat remains trapped in the city. Here it is especially important to emphasise that urban geometry plays a role in retaining this energy in the urban atmosphere. Street canyons do not allow energy to leave the area, trapping it and leading to an increase in city temperatures. Another source of heat playing an important role is anthropogenic heat, i.e. the heat generated by the exhaust gases of cars and refrigerating appliances, which intensifies UHIs' effects.

At night, UHIs' effects are more pronounced as artificial surfaces absorb all incoming solar radiation during the day and emit it at night in the form of longwave radiation. Therefore, unpleasantly high night temperatures in cities are common during the summer months, which increases heat risk, especially for vulnerable groups such as children and the elderly.

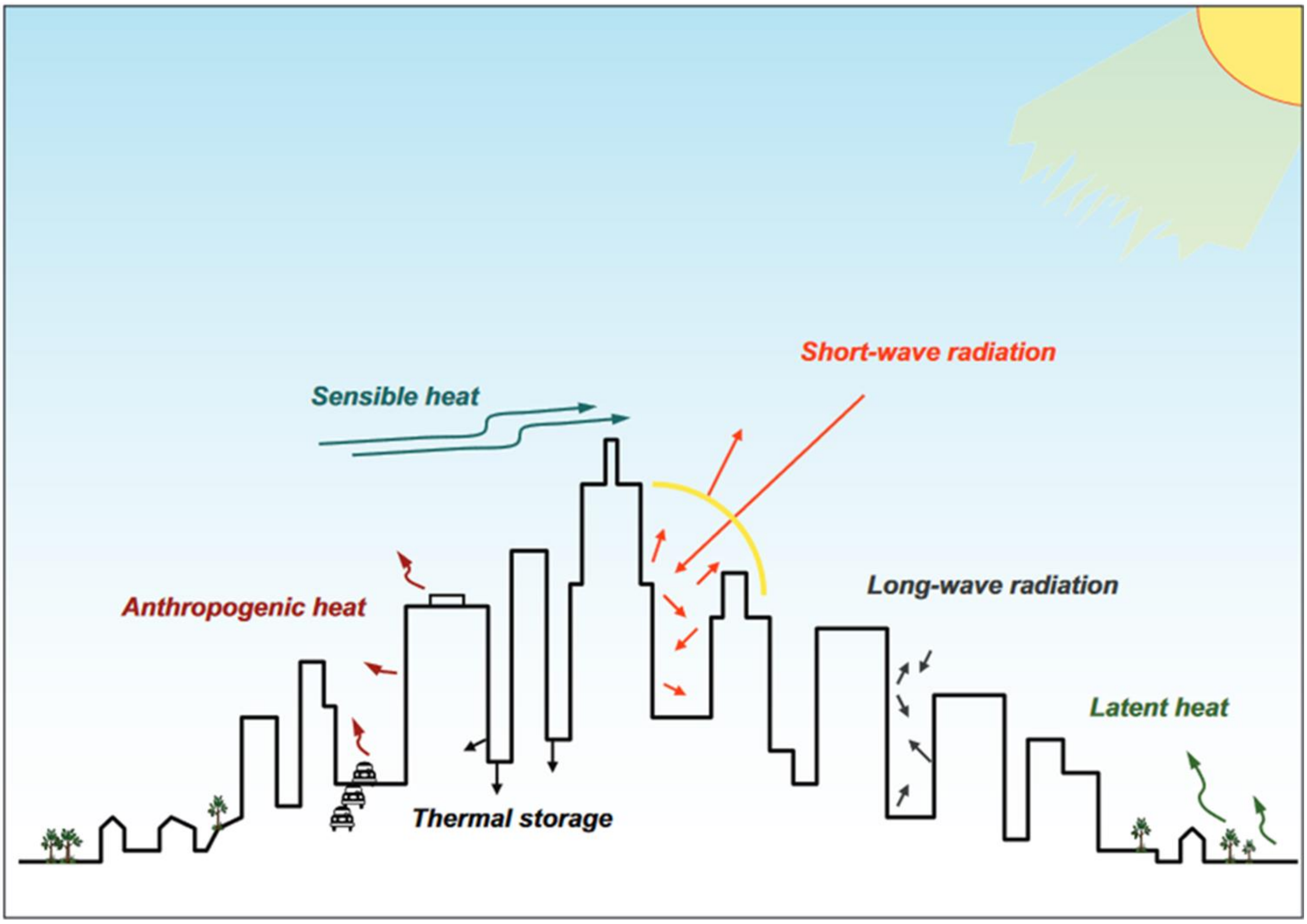


Figure 11 Urban Energy Balance (US EPA, 2008.)

Basic starting points for UHI identification and mapping methodology selection:

- The methodology in the first phase should be relatively simple, should not include additional satellite or other more complex measurements, and may include additional data (from local stations, satellite imagery, etc.) in the upgrade phase or in cases of local availability.
- The methodology should enable analyses of the current state of land cover and heat load for all local self-government units in Croatia, which implies the availability of data at national level.
- The method used for intensity identification and mapping should be appropriate and compatible for use in the Green Infrastructure Registry of the Republic of Croatia (Table 4), i.e. it should provide an overview of UHIs with the aim of defining and implementing measures to combat UHIs (especially those measures related to the development of green infrastructure in cities).

Green Infrastructure Typology Classes	
1	Park
2	City/Urban forest
3	Sports and recreational area
4	Meadow
5	Botanical garden/Arboretum/ZOO
6	Historical garden
7	Green constructive elements on buildings
8	Productive green infrastructure - urban gardens, urban farms, greenhouses, public orchards
9	Integrated urban drainage systems
10	Urban wetland
11	Park cemetery
12	Brownfield area
13	Watercourse, wetland, riparian zone and surface inland waters
14	Square
15	Sea coast
16	Touristic zone
17	Green areas next to residential buildings
18	Green areas next to public, social and economic buildings
19	Theme park
20	Archaeological park
21	Green traffic corridors
22	Planting trees

Table 4 Classification of green infrastructure typologies in the Green Infrastructure Application Manual. Summarised on the basis of: Ministry of Physical Planning, Construction and State Property, 2023.

DESCRIPTION OF METHODOLOGY

In view of the abovementioned basic starting points, **a methodology that combines available data on land use, aerial imaging data and mathematical modelling of solar radiation is proposed.**

As the basic spatial piece of data for UHI mapping, it is possible to use the map of vegetation and land type available in the form of basic topographic database (BTD) which are made in accordance with the CROTIS methodology and are within the scope of authority of the State Geodetic Administration. These data are available on request and mapped in the 1:10.000 scale, which is currently the only data of this type and detail available for the entire territory of the Republic of Croatia. Satellite measurements would allow mapping categories from BTDs with UHI impact categories.

BTDs shall contain a description of the land cover at any point of the surface, thus identifying areas with natural cover and those with constructions. This base also specifies the purpose/type of human activity. As previously mentioned, human activity has the greatest impact on the UHIs’ emergence, so understanding the surfaces we have built and our activity in different areas is crucial to conclude which anthropogenic elements contribute more to an increased thermal risk than others.

Cover and land use under BTD (Table 5) covers the following categories:

- Agricultural land
- Forest area
- Tree
- Tree line and hedge
- Other natural areas
- Economic territory
- Public spaces
- Special purpose areas
- Land use.

Category in accordance with BTD	Contribution to the UHI emergence

Agricultural land	Although agricultural land is of natural origin, due to the high exposure to solar radiation, agricultural areas often have similar or even higher temperatures compared to urban areas. In addition to that, they are not covered with greenery all year round, but rather come in the form of bare land, contributing to rising temperatures. Understanding these areas is extremely important because farmers spend a lot of time outdoors, exposed to heat.
Forest area, tree, tree line and hedge, other natural areas	High vegetation allows surfaces to cool naturally through processes such as evapotranspiration. Trees and natural surfaces absorb the sun's energy, but evaporate water through their leaves, which helps cool the environment. Therefore, areas under natural cover are cooler than urban areas.
Economic territory	Urban surfaces such as industrial zones are characterised by a high proportion of asphalt, concrete, metals and other artificial materials, as well as a low proportion of greenery. In addition, heat emissions from industrial processes further increase the thermal risk of these areas. Such areas refer to the most common parts of the city with the highest temperatures and they need to be carefully analysed as many citizens work and live in them.
Public spaces	Public spaces are the most important category, as citizens gather in them the most in their free time. As a rule, they are characterised by artificially made or arranged surfaces, usually with solid cover such as asphalt and concrete. Such areas include squares, commercial surfaces, areas for sport and recreation, yards etc. Public areas are a rather diverse category, and each of the elements they consist of should be analysed separately.
Special purpose areas	They are mostly made up of objects used for defensive purposes.
Land use	Category covering areas of specific human activity, e.g. bus and train stations, road service areas, sports and recreation sites, as well as other areas where the population often spends time.

Table 5 Description of cover and land use categories in accordance with the BTD

As for taking aerial images, the digital surface model created on the basis of multi-sensor aerial imaging of the Republic of Croatia, which resulted in LiDAR recordings, can be used for that purpose.

When the algorithm for the calculation of solar radiation is used, it is possible to mathematically define the amount of radiation per surface unit. One of the tools which may be used for this purpose is the *Modelling solar radiation*[82] system, which calculates the sum of direct and diffuse radiation, and takes into account the topography of the terrain, the construction and the presence of certain elements that affect the amount of radiation.

By overlapping cover layers and land use according to the BTD, when solar radiation is calculated and the GIS spatial analysis tool is used, it is possible to identify areas with a potential UHI emergence.

This method has some shortcomings, such as the temporal update of BTDs and insufficient level of detail, but it is proposed as a basic methodology with regard to the availability of data in Croatia. In case other data is available at the level of local government units (hereinafter: LGUs), such as those from temperature sensor networks, it is possible to carry out a more detailed identification procedure.

Furthermore, it is also possible to use publicly available and comparable data at the EU level for LGUs for which these data are available. One example of such data is the Urban Atlas Land Cover/Land Use 2021 that exists within the frames of the Copernicus programme.[83] Possible additional methods are described in more detail below.

[82] Tool reference: Modelling solar radiation: https://pro.arcgis.com/en/pro-app/3.1/tool-reference/spatial-analyst/modeling-solar-radiation.htm
[83] Urban Atlas Land Cover-CLSM, 2021: https://land.copernicus.eu/local/urban-atlas/urban-atlas-2018

ADDITIONAL POSSIBILITIES FOR UHI IDENTIFICATION AND MAPPING METHODS

Depending on availability, other methods explained below may be used as an upgrade of the basic UHI identification and mapping methodology.

USE OF METEOROLOGICAL STATION DATA

The first step in this process is the use of data collected by the official meteorological stations of the Croatian Meteorological and Hydrological Service. However, not all LGU's have a meteorological station within their administrative boundaries, and the stations they have are often not located within built-up areas, but on the outskirts of the city. As a result, the impact of UHIs cannot always be registered. In order to compensate for the lack of official stations, LGUs are advised to invest in the installation of a temporary network of meteorological instruments in order to collect extremely important data on the distribution of heat in the city during certain periods. More specifically, the installation of such instruments would help define sites that are extremely hot and where the implementation of adaptation measures is required. The range of instruments available on the market is large and the ratio between the quality of the data obtained and the assets invested is very good. Examples of such adaptation measures include the Citizen Weather Stations set by amateur observers, for example, in their own garden. Owners can enter the results of their observations via online platforms, making them available to different applications.[84]

CLASSIFICATION OF LOCAL CLIMATE ZONES

By collecting and analysing high-resolution data, it is possible to gain insight into the spatial distribution of surface temperatures throughout different LGUs. It is important to emphasise that the surface temperature differs from the air temperature measured by meteorological stations. It is also necessary to analyse the link between the measured temperature (air or surface temperature) and cover and the use of land. For this purpose, the use of local climatic zones (LCZ) is possible. Since the thermal characteristics of individual parts of a city may differ due to different building density rate, a classification type that takes into account the local characteristics of individual city parts has been developed. LCZs are areas of uniform land cover, urban structure, building materials and similar human activities that stretch from several hundred meters to several kilometres on a horizontal scale.[85] This type of classification defines ten classes of plot ratio (three classes of compact construction depending on the height of the buildings, areas with single-storey buildings, scattered construction in the natural environment, industrial areas) and seven classes of land cover (areas with dense tall vegetation, areas with sparse tall vegetation, areas with shrubland vegetation, areas with grassy and herbaceous vegetation, stone or paved areas, earthy or sandy areas, water surfaces) – see Figure 13. It is a classification that defines the same characteristics for individual classes, and its greatest advantage is the fact that it is applicable regardless of the location of the city, thus enabling the possibility of city comparison. The data on LCZs (Figure 12) from the whole world are freely available, and thus include the areas of local self-government units in Croatia.[86] The data are available in a TIFF data format that is compatible for use with GIS tools, given that further analyses are carried out.

[84] World Bank, 2020

[85] Stewart and Oke, 2012

[86] Local climate zones available at: https://zenodo.org/records/8419340

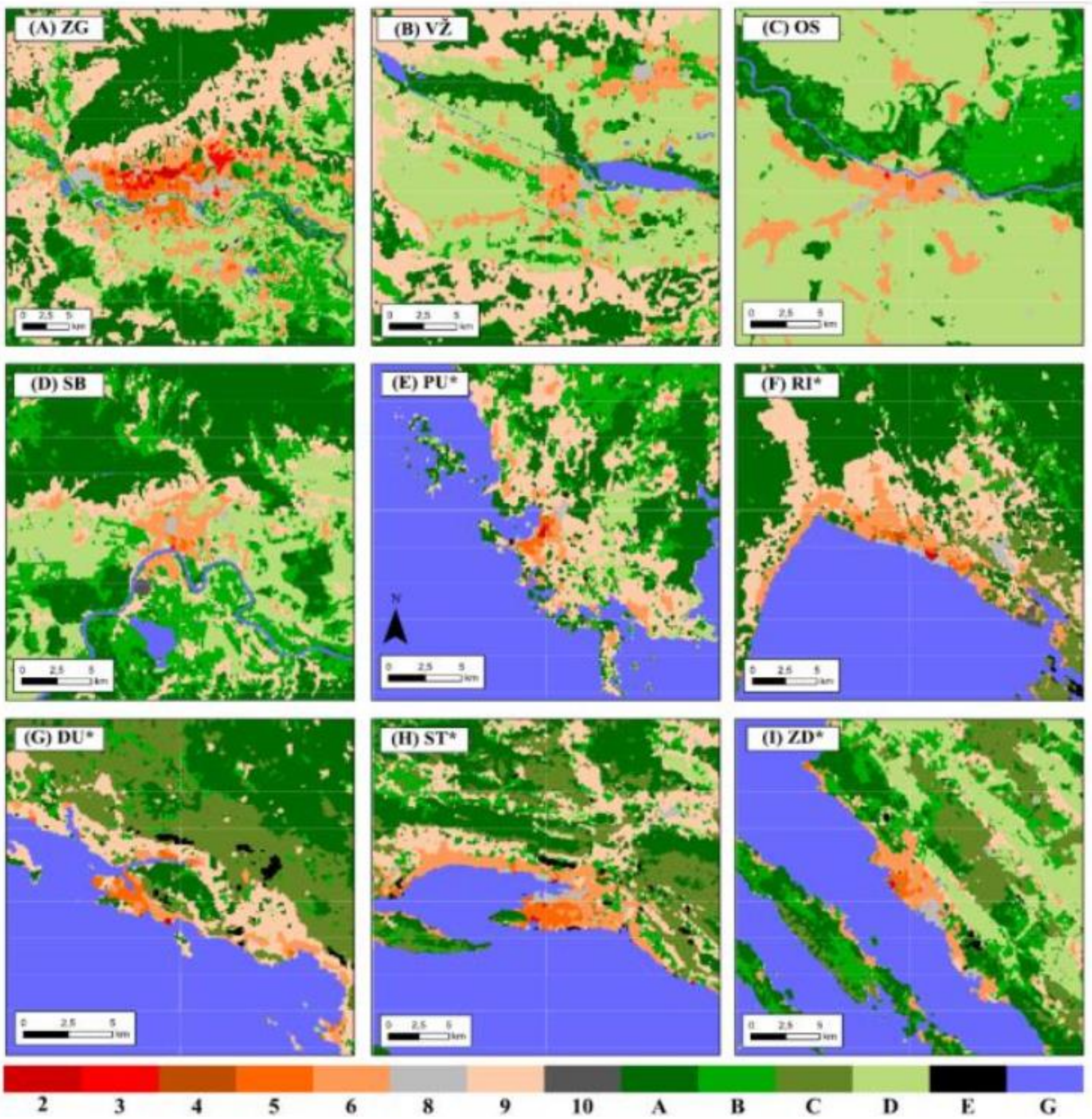


Figure 12 Local climate zone in nine Croatian cities (Žgela et al., 2024)

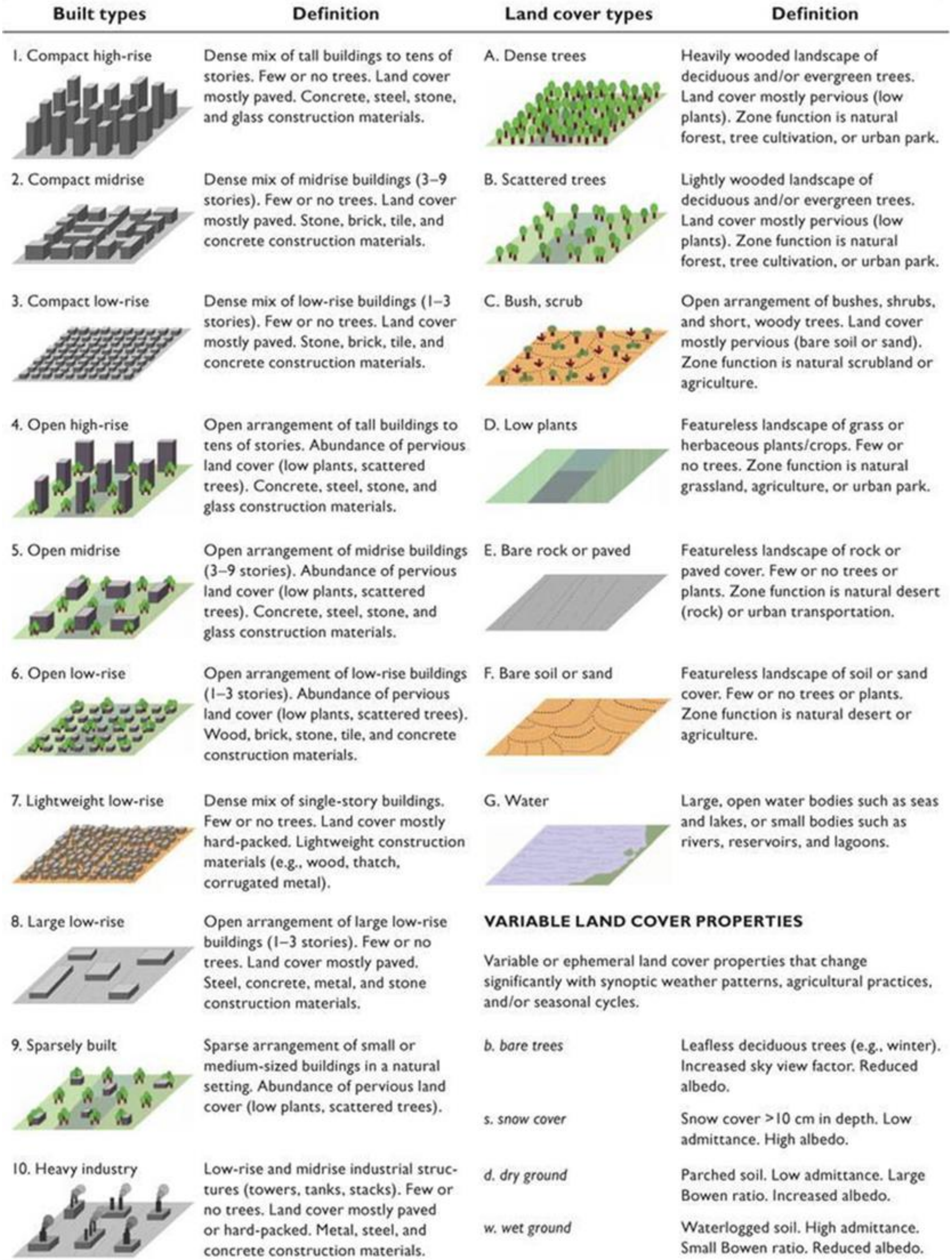


Figure 13 Classification of local climate zones (Stewart and Oke, 2012)

Integration of local climate zones and surface temperatures

Since local climate zones describe microclimatic conditions in cities and their surroundings, they are an optimal tool for the detection of UHI impacts. With their help, it is possible to calculate the zonal characteristics of specific parts of the city, i.e. the spatial distribution of heat.

Data on surface temperatures in the whole world, including Croatia, have been publicly available in high spatial resolution since the 1980s. Thus, they enable and help determine the temporal and spatial heat changes of a particular urban area. The data is available on the United States Geological Service (USGS site).[87] Downloading data from it is easy and user-friendly.

Steps to data download

Figure 14 Selection of temporal and spatial scope of research

1. Register via the following site: https://earthexplorer.usgs.gov/.
2. Select ‘World features’ in the menu and enter the name of the LGU (Figure 14) you would like to see.
3. Select the period for which the data is needed.

Figure15 Overview and download of surface temperature data

4. Select “Data sets” (Figure15).

[87] United States Geological Service, USGS; available at: https://earthexplorer.usgs.gov/

   a. At this point, the high spatial resolution data of the Landsat satellite mission, which provides information on surface temperature from 1984 to the present, is downloaded. It is possible to select any of the three satellites listed as each offers data for a different period of time.
   b. Once the satellite is selected, press “Results”.
5. Select the desired satellite image.
   a. It is necessary to check if the clouds cover the chosen LGU area. In case they do, there will be no surface temperature data, so another cloudless satellite image should be selected.
   b. After searching, click on “Download options”, thus opening a new window
   c. Select “Level-2 Surface Temperature Bands”.
      i. The selected data is downloaded in a TIFF data format that can be opened in any GIS software, e.g. ArcGIS or QGIS.
      ii. The surface temperature layer is named after the satellite scene and ends in *ST_Band10.tif.* Since the data in question is “raw”, a simple calculation of values in degrees Celsius should be conducted, which can be accomplished with the help of the Raster Calculator option in the GIS software.

         LST (°C) = (LST (raw) * 0.00341802 + 149) – 273.15

The last step is to display the surface temperature in the GIS software you have chosen and in the selected colour scale, which allows you to spot high temperature locations. Additionally, by overlapping layers of local climatic zones and surface temperature, it is possible to calculate UHI effects with the help of the “Zonal statistics” tool.[88] The result is displayed in a table containing surface temperature statistics per class of local climatic zones.

[88] Tool: Zonal statistics; available at: https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/zonal-statistics.htm

URBAN ATLAS

The European Urban Atlas[89] provides an insight into the morphological features of cities, such as building density or land use in them, and its typology is shown in Table 6. It is important to emphasise that the Urban Atlas data cover six urban areas in Croatia, so it cannot be used for all LGUs at the moment.

Class code	Nomenclature
11100	Continuous Urban Fabric (Sealing Degree > 80%)
11210	Discontinuous Dense Urban Fabric (Sealing Degree 50% - 80%)
11220	Discontinuous Medium Density Urban Fabric (Sealing Degree 30% - 50%)
11230	Discontinuous Low Density Urban Fabric (Sealing Degree 10% - 30%)
11240	Discontinuous Very Low Density Urban Fabric (Sealing Degree < 10%)
11300	Isolated Structures
12100	Industrial, commercial, public, military and private units
12210	Fast transit roads and associated land
12220	Other roads and associated land
12230	Railways and associated land
12300	Port areas
12400	Airports
13100	Mineral extraction and dump sites
13300	Construction sites
13400	Land without current use
14100	Green urban areas
14200	Sports and leisure facilities
20000	Agricultural + Semi-natural areas + Wetlands
30000	Forests
50000	Water bodies

Table 6 Nomenclature of land categories by purpose from the Urban Atlas database in English. Summarised in accordance with the EEA, 2021.

Below is an overview of the methodology used when the data from the Urban Atlas are available. The methodology encompasses remote sensing of soil temperature with the necessary adaptation to the specific Croatian context and in accordance with the defined preconditions for the development of the methodology. The data on surface temperature should actually be linked to data on land use and utilisation in accordance with the appropriate category of the Urban Atlas. For each category defined, it is necessary to make a calculation of the average temperature. It is also necessary to calculate average temperatures for individual categories in accordance with the defined Green Infrastructure Typology. Green infrastructure categories must be complemented by the built-up area categories covered by the landscape classification methodology used in the Atlas.

For a precise calculation of UHIs effects at different locations in the city, the temperature of the selected locations should be measured accurately. As satellite data (such as those produced by Landsat-5) with temperature maps of a resolution high enough to fulfil our needs were not available, we advise using reference temperature values for individual land types, i.e. applying the results that were used in the calculation of UHI effects for different types of land per cover and use in Maribor. The reference categories of effects for different types of land in Maribor (with awareness of the limitations of this methodology) that were thereby obtained can be used to map UHI effects in Croatian cities as well.[90] Furthermore, data on the current stage of land use are also based on the Green Infrastructure Registry and[91] are complemented by more relevant and detailed categories of built-up land, such as those in the Urban Atlas[92].

As the impact of UHIs represents the difference in the temperature of urban areas and surrounding rural areas, this methodology proposes to identify UHIs as follows: UHIs effect at a given location within a city can be identified if the difference between the temperature of that location and the temperature outside the city is greater than or equal to 2 C ($\Delta T \geq 2$ C).

UHI mapping implies a spatial representation of UHIs' recorded effects. Mapping does not simply imply the presence and intensity of UHIs have been recognised with the purpose of establishing a visual display of their distribution in space and the extent of temperature variations within the urban landscape. Mapping is based on a Geographic Information System (GIS) and cartographic techniques applied for the purpose of visual

[89] EEA, 2021
[90] Žiberna and Ivanjšič, 2022
[91] Ministry of Physical Planning, Construction and State Property, 2023
[92] Copernicus Land Monitoring Service, 2021

representation of the forms and exposure of UHIs. Mapping provides a comprehensive perspective allowing participants to understand the spatial relationships and implications of UHI effects on the urban environment and its population.

THEORETICAL BASIS, ASSUMPTIONS AND LIMITATIONS OF THE MAPPING METHODOLOGY:

- The input data we are working with is the Green Infrastructure Registry. Based on the existing Green Infrastructure Registry, mapping UHIs effects is, first and foremost, not possible, as green infrastructure in itself reduces these effects. The morphological elements, i.e. categories caused by UHIs, in the Green Infrastructure Registry are not specified with sufficient precision.
- In order for the Green Infrastructure Registry to be used for the purpose of identifying and mapping UHI effects, it needs to be updated with data on urbanisation density. To accomplish this, various spatial data sources can be used, such as Corine Land Cover[93] or Urban Atlas[91]. For a maximally precise mapping process, spatial resolution of the land category should be as high as possible, e.g. the Corine Land Cover base has a spatial resolution of 100 m, whereas the Urban Atlas has the highest possible resolution of 10 m.
- In order for us to carry out the UHI mapping based on the Croatian data that is currently available, it is proposed to use the procedure presented below. The Green Infrastructure Registry, defined precisely enough for 22 open spaces, as well as green and blue area typologies, is connected to the Urban Atlas network. In further research of this area, a spatial-resolution scale that is more precise than the Urban Atlas scale can be used. Ideally, a map would be available for individual infrastructure elements with a spatial resolution of 10 m or higher.

URBAN HEAT ISLAND MAPPING PROCEDURE

UHI mapping is usually carried out using input data on land use, with the typologies of the Green Infrastructure Registry being used first. As the name suggests, the Green Infrastructure Registry primarily refers to green areas. In order to identify UHI effects in accordance with the green infrastructure typology, a supplementation of the typology with the appropriate classes of the built-up areas which are defined in the Urban Atlas, but not in the existing green infrastructure typology, is advised. For this purpose, as shown in Table 6[89],UHI effect categories shall be used as a benchmark

Note 1: *The green infrastructure typology is essentially a classification of certain categories of open areas which are more detailed than the Urban Atlas, meaning it does not replace the categories unambiguously. However, we aim to present UHI effects in different categories of green infrastructure. For this purpose, the Urban Atlas Mapping Guide[94] is used, as the green infrastructure categories are contained within the categories of the Urban Atlas.*

Note 2: *Using a different approach for these categories of the Urban Atlas was very important, as there were no UHI value calculations for certain categories.[89] The results of the analysis were used for the classification of the missing categories in accordance with their contribution to UHI effects.[95] Categories that are only classified by the level of contribution to UHI effects are shown in Table 7 under the "/" sign in the column "UHI impact".*

Categories of land use according to the Urban Atlas	Land use categories according to the typology of the Green Infrastructure Registry	UHI impact [°C]
1110 Continuous urban fabric (S.L. > 80%)	14 Square	4
1210 Industrial, commercial, public and military units	9 Integrated urban drainage system	3.7
1223 Railways and associated land	/	3.3
1121 Discontinuous dense urban fabric (S.L.: 50%–80%)	/	3.1
1222 Other roads and associated land	/	2.2

[93] European Environment Agency, 2018.
[94] Copernicus Land Monitoring Service, 2020.
[95] Boras et al., 2022.

Categories of land use according to the Urban Atlas	Land use categories according to the typology of the Green Infrastructure Registry	UHI impact [°C]
1122 Discontinuous medium density urban fabric (S.L.: 30%–50%)	/	2
1340 Land without current use	12 Brownfield area	1.9
1330 Construction sites	/	/
1310 Mineral extraction and dump sites	/	1.2
1221 Fast transit roads and associated land	21 Green traffic corridors	1.2
1420 Sports and leisure facilities	03 Sports and leisure areas, 16 Touristic zone, 19 Theme park	1.2
1410 Green urban areas	01 Park, 05 Botanical garden/Arboretum/ZOO	1.1
1240 Airports	/	/
1230 Port areas	/	/
1123 Discontinuous Low Density Urban Fabric (S.L. : 10%–30%)	07 Green constructive elements on buildings, 17 Green areas next to residential buildings	0.6
2100 Arable land	/	0.5
2500 Orchards at the fringe of urban classes	08 Productive green infrastructure – urban gardens, urban farms, greenhouses and public orchards	/
2200 Permanent crops (vineyards, fruit trees)	22 Planting trees	0.5
1124 Discontinuous very low density urban fabric (S.L. < 10%)	06 Historical garden, 11 Park cemetery, 18 Green areas next to public, social and economic buildings, 20 Archaeological park	0.4
3300 Open spaces with little or no vegetation (beaches, dunes, bare rocks, glaciers)	15 Sea coast	/
2400 Complex and mixed cultivation patterns	/	/
3200 Herbaceous vegetation associations (natural grassland, moors...)	/	/
2300 Pastures	04 Meadow	0
1130 Isolated structures	/	-0.2
3100 Forests	02 City/Urban forest	-1.8
4000 Wetland	10 Urban wetland	/
5000 Water bodies	13 Watercourse, wetland, riparian zone and surface inland waters	-2.6

Table 7 UHI impact during summer in accordance with Urban Atlas categories and Green Infrastructure Typology

Mapping procedure: the user will download the necessary input data, such as land categories per purpose as defined by the Urban Atlas and green infrastructure elements, using the GIS programme, and then record these categories in accordance with the UHI impact categories displayed in Table 7.

Below is an example of the results of the UHI impact map for the City of Zagreb (Figure16). It is apparent that the categories with the highest impact (ΔT ≥ 2°C) are as follows:

- Continuous urban fabric (S.L. > 80%) (UHI = 4°C)
- Industrial, commercial, public, military and private units (UHI = 3.7°C)
- Railways and associated land (UHI = 3.3°C)
- Discontinuous dense urban fabric (S.L.: 50%–80%) (UHI = 3.1°C)
- Other roads and associated land (UHI = 2.2°C)
- Discontinuous medium density urban fabric (S.L.: 30%–50%) (UHI = 2°C).

On the other hand, the categories that actually have a UHI mitigation effect are:

- Water bodies (-2.6°C compared to pastures)
- Wetlands, forests (-1.8°C compared to pastures)
- Isolated structures (-0.2°C compared to pastures)

Figure16 Example of a UHI effects map for the City of Zagreb with the associated UHI categories in accordance with the Urban Atlas and the Green Infrastructure Registry

Maps showing the spatial distribution of UHI effects allow us to get a better understanding of temperature variations in urban areas. As previously mentioned, maps can be created using the GIS programme and Table 7 for the purpose of connecting UHI effects to different green infrastructure categories, complemented by the Urban Atlas categories.

For the purpose of presenting UHI effects within the Physical Planning Information System (PPIS), it is recommended to create a new layer called "The thermal urban island effect," which would include maps such as the one shown in Figure 16.

UHI effect maps allow users to analyse, interpret and use spatial data on UHI effects via GIS software. They are a source of important data on temperature differences within cities, which can be useful in the process of urban planning, adoption of climate change adaptation measures, and mitigation of heat hazards.

Potential restrictions on the use of the Urban Atlas and overlap with the Green Infrastructure Registry

- The Urban Atlas for the territory of Croatia refers to six urban areas – more specifically, Osijek, Rijeka, Slavonski Brod, Split, Zadar and Zagreb, including the given cities and local self-government units that surround them or jointly form urban areas. Thus, only certain LGUs can access the Urban Atlas for the purpose of improving basic methodology.
- Furthermore, a complete overlap between the Green Infrastructure Registry and the categories defined by the Urban Atlas is not possible because the Urban Atlas typology elaborates green and other open areas in more detail, whereas the Green Infrastructure Registry only lists areas located within the construction area of the settlement.
- The minimum mapping width in the Urban Atlas, e.g. for categories 14100 Green urban areas and 14200 Sports and leisure facilities, is 10 m. However, the minimum mapping width in the Green Infrastructure Registry is greater because it represents a more detailed database at the level of each LGU. The same goes for the minimum mapping surface, which varies from 0.25 to 1 ha in the Atlas.
- Although certain categories of the Urban Atlas correspond with the individual typologies of the Green Infrastructure Registry, by nature, they do not represent the same areas, with one type of area in the Green Infrastructure Registry potentially referring to several categories in the Atlas. For example, category 14200 Sports and leisure facilities covers several types and/or subtypes in the Green Infrastructure Registry, such as Sport and leisure areas, Tourism zones i.e. Camps, Urban Gardens, etc.
- It is partly possible to include certain typologies from the Green Infrastructure Registry into the Atlas categories, but it should be borne in mind that the level of detail, the method of mapping and categorisation in the two systems are not the same. Some examples with notes:
    - 14100 Green urban areas – Park, Botanical garden/Arboretum/ZOO, Historical garden, Park cemetery, Sports and recreational areas (subtype: children's playground), Archaeological park
    - Note – In the Urban Atlas, areas with vegetation that are smaller than 0.25 ha are merged with the surrounding categories, whereas areas whose surface ranges from 0.25 to 1 ha are classified into category 13400 Land without current use. On the other hand, the Green Infrastructure Registry provides more detailed mapping, even classifying areas with a surface smaller than 0.25 ha.
    - 14200 Sports and leisure facilities – Sports and recreational facilities, Productive green infrastructure – urban gardens, urban farms, greenhouses and public orchards[96], Theme park, Touristic zones
    - 31000 Forests – City/urban forest
    - Note 1 – Urban Atlas also includes nurseries into category 31000, whereas the Green Infrastructure Registry places them in a separate category (Productive green infrastructure – urban gardens, urban farms, greenhouses and public orchards).
    - Note 2 – According to the Urban Atlas, forests located in urban areas are categorised as 14100 Green urban areas.
    - Note 3 – Minimum mapping unit for urban forests is 1 ha.
    - 23000 Pastures – According to the Urban Atlas, this category includes pastures and meadows used for agricultural purposes, and according to the Green Infrastructure Registry grasslands include ornamental and usable Lawns on publicly accessible areas.

The limitation within the frames of direct connection between different land categories in the Urban Atlas on the one hand and the Green Infrastructure Registry on the other is particularly evident when it comes to private spaces, since private gardens are not registered as green areas in the Atlas, but are part of the categories depicting urban tissue (e.g. continuous and discontinuous urban tissue). For example, the Green Infrastructure Registry includes green areas adjacent to public, social and economic buildings and green areas adjacent to residential buildings. Attempting to directly overlap and map UHIs without taking this fact into account is likely to result in erroneous results, i.e. misinterpretation of the data.

[96] Urban Atlas defines urban vegetable gardens as complexes of several to several hundred land parcels intended for population use, in which most parcels contain individual agricultural areas with fruit or vegetables, as well as a storage for tools and shelters, and as such places them in category 1.4.2. Sports and leisure facilities.

Other update options and alternative methodology approaches

- For further work, we suggest planning precise temperature measurement procedures at different locations within Croatian cities. This would allow updating UHI intensity categories implemented by Žiberna and Ivanjšič,[97] which we use in the current version of the methodology, with UHI impact size categories measured on the basis of Croatian cities. Nevertheless, the calculations referring to UHI effects for different types of land by use in Maribor are currently the best source of data we have.

- Moreover, the next phase of methodology development, which is presented in this document, could include the use of land classification of higher spatial resolution (the spatial resolution limit in the Urban Atlas is currently 10 m). In the final stage of the mapping methodology development, it is necessary to base the mapping on the individual elements within the land use categories.

- Furthermore, the upgrade of the methodology could include an additional set of data from the Copernicus Land Monitoring Service, more specifically, data on the height of buildings in cities.[98] At the moment, only the 2012 data are available, meaning an updated version has only yet to come.

- Due to the extremely negative impact of heat emissions of refrigerating appliances, in particular refrigeration units within large complexes and places of public gatherings, such as shopping malls, we advise introducing a mapping procedure for refrigerating units in order to more accurately predict UHI emergence and intensification.

In conclusion, it can be stated that there are a number of methodologies focused on studying UHIs in various ways. They differ by their research focus/objective, input data, precision and complexity. The three most commonly used methods are numerical modelling, analysis of remote sensing data and field measurements.

Taking into account all the specificities of Croatian territory and sources, availability and structure of available data, a methodology has been proposed. The proposed methodology combines data on land use (basic topographic database, BTD), data from multisensor aerial imaging of Croatia, and mathematical modelling of solar radiation.

As an option for further development, we propose considering the implementation of modelling procedures based on the use of remote sensing data on surface temperature and comparing them with data on land use and cover.

---

[97] Žiberna and Ivanjšič, 2023
[98] EEA, 2022

MONITORING CHANGES IN INTENSITY

MONITORING CHANGES IN INTENSITY

In Croatia, short, medium and long-term monitoring of changes in UHI intensity requires systematic research tailored to the specificities of different regions and settlements. For the purpose of efficient monitoring of UHI effects in Croatia, a list of research guidelines shall be proposed below.

MONITORING INTERVALS – RECOMMENDATIONS

SHORT-TERM MONITORING (DAILY TO MONTHLY)

- Collect daily temperature data from meteorological stations to monitor short-term fluctuations in UHI intensity.
- Analyse satellite images with data on average surface temperature on a monthly basis to identify seasonal trends in temperature change and UHI emergence.
- Carry out periodic mobile research to identify dynamic changes with regard to UHI intensity within urban areas.

MID-TERM MONITORING (SEASONAL TO ANNUAL)

- Compile daily air temperature data during the seasons to estimate seasonal variations in UHI intensity.
- Perform a quarterly analysis of satellite imagery to track changes in soil surface characteristics and size of the UHI.
- Carry out annual analyses of urban morphology in order to monitor long-term modifications in land use and form, as well as the layout of the built-up space.

LONG-TERM MONITORING (MULTIANNUAL)

- Compress multiannual temperature datasets to identify long-term trends in UHI intensity.
- Use previous satellite imagery to analyse decades of changes in urban heat patterns and land use dynamics.
- Implement periodic surveys on the perception of residents' living comfort every few years to assess the effectiveness of UHI mitigation measures and urban interventions.

ADAPTATION TO THE CROATIAN CONTEXT

COASTAL URBAN AREAS

- Focus on monitoring UHI intensity in coastal cities with a high building density, taking into account the impact of marine air flows on local temperature patterns.
- Focus on short-term monitoring during the summer months, when UHI effects are the most pronounced.
- Include mid-term monitoring to assess the impacts of tourism and seasonal influx into the area on changes in UHI characteristics.

CONTINENTAL URBAN AREAS

- Focus on long-term monitoring with the purpose of detecting gradual changes in UHI intensity due to urbanisation and infrastructure development.
- Carry out mid-term monitoring during the winter months to create a better understand of the variations in UHI effects caused by heating.
- Consider the impact of surrounding agricultural land on the emergence and expansion of UHIs.

MEASURES TO MITIGATE THE EFFECTS OF URBAN HEAT ISLANDS

MEASURES TO MITIGATE THE EFFECTS OF URBAN HEAT ISLANDS

The negative effects of the expansion of high density settlements, such as increases in urban space temperatures and more frequent and longer-lasting heatwaves, will intensify, so it is necessary to implement measures to reduce energy consumption and protect the environment and human health in cities.[99] These topics have been addressed through the scientific research of Rojas-Fernández et al., Santamorius and Yun and many others.[100] Among the various urban planning and design strategies for more resilient cities, the most studied topics in the scientific literature[101] in this regard are the use of evaporative systems and soil shading, as well as the introduction of green infrastructure, air and soil heat exchangers and reflective technologies. When implementing UHI mitigation strategies and measures, it is necessary to focus on nature-based solutions. Furthermore, educational activities at all levels can significantly help reduce UHI effects. However, many citizens are not yet sufficiently aware of environmental problems arising in conditions of high heat load. Investing in the education of city dwellers can encourage citizens to actively participate in the reduction within their own home, and help strengthen the integrity of the community.

When it comes to the development of quality and climate-neutral settlements and adaptation to climate change, spatial planning and construction processes should focus on:

- providing a sense of safety in the face of climate change risks (droughts, fires, floods, landslides)
- ensuring water availability needs and sustainable water management (water retention measures, reuse of rainwater, deregulation of regulated watercourses, etc.)
- securing the accessibility of green areas with diverse ecosystem services (planning and development of high-quality, accessible, connected green spaces and other nature-based solutions, including blue infrastructure elements)
- helping to cool settlements, urban spaces and buildings (morphological form of built-up settlement parts, ventilation, building density, relationship between built-up areas and areas that were not built on)
- conducting circular management of space and buildings (impact on reducing demand for new building sites and expansion spaces, as well as natural materials)
- incorporating sustainable mobility elements (decrease in the share of motorised traffic, multi-purpose use of parking and space, efficient pedestrian and cycling infrastructure)
- ensuring the use of renewable energy sources and energy efficiency.

The following part of the document contains proposals for UHI mitigation measures in accordance with the following categories:

- **Green and blue infrastructure**
- **Urban design elements**
- **Technological measures.**

[99] Carnielo and Zinzi, 2013
[100] Rojas-Fernández, Galán-Marín and Fernández-Nieto, 2017; Santamouris and Yun, 2020
[101] Santamouris et al., 2017; M. Taleghani, 2018

GREEN INFRASTRUCTURE

The use of urban green infrastructure (UGI) can partially mitigate UHI effects, increasing the resilience of urban spaces to climate change. In order to achieve this, UGI needs to be systematically integrated into urban planning and legislation. However, this process depends on the availability of widely applicable, easily accessible and quantitative evidence.

UGI has been acting as a positive factor influencing temperature reduction in European cities by an average of 1.07°C, and a possibility of reaching as much as 2.9°C. To achieve a 1°C urban temperature reduction, the amount of tree canopy cover should reach at least 16%. The regulation of the microclimate mainly depends on the amount of vegetation within a city, as well as the rates of tree canopy and soil moisture evaporation. Furthermore, more than half of the population in almost 40% of European countries does not benefit from the microclimate regulation enabled by urban vegetation. The broad implementation of the UGI, especially in arid regions and in cities with an insufficient rate of tree canopy cover, is key to ensuring healthy living conditions for the urban population.

Using nature-based solutions (NBS) has a positive impact on UHI mitigation, but also on a number of other related factors, such as biodiversity conservation, impact on citizens' health and cognitive abilities, energy savings and many others. Moreover, apart from the spatial components, the interaction of the environment and different types of NBS entails a temporal component, as well, which further points to the complexity of measuring and evaluating the efficiency of investments in such solutions. For this reason, it is necessary to standardise reliable methods for the evaluation of the effectiveness of investments in line with local specificities, in addition to developing new NBS integration methods.

When discussing UHI negative effects, it must be emphasised that habitats, i.e. urban soil, as an indispensable part of the NBS system complexity, also have a significant impact on the efficiency of their reduction. Characteristics of different habitats can have a significant negative impact on the rates of water transpiration through plant organs growing above ground, which has a twofold negative impact on UHIs, but also on the survival and resilience of the plants themselves. This impact, although known, is ignored due to the increased cost of using NBS through the employment of the underground pit method. However, compensating this by planting larger quantities of same species will only worsen the situation in the long run, as it may lead to a significant increase in the cost of maintenance, as well as encourage competition for space both under and above ground and for the biogenic elements and available moisture between the elements of urban greenery. In other words, in addition to the spatial component of tree canopy cover, the focus should also be put on the temporal component of long-term cover development, as well as on the sustainability of UGI development strategies.

In view of the previously mentioned restrictive factors, the text below shall provide an overview of the interaction between the environment and nature-based solutions, in the form in which they are found in UGI typology. This shall be followed by guidelines on mitigating UHI effects.

Measures for the successful mitigation of UHI effects need to be adapted to the specific purpose of the categories and to the specific location of individual sites. That is why it is important to apply a multidisciplinary approach while considering other factors that occur in a given space primarily or secondarily.

Simple UGI elements include:

2.1. Parks and urban forests

- Expanding parks and urban forests helps reduce UHI effects through shading, surface temperature reduction and increased environmental cooling through evaporation and transpiration effects.
- Planting trees and expanding tree canopy cover areas within urban forests and parks reduces the absorption of sun rays and consequently the temperature of the environment.

2.2. Wide avenues and streets with trees

- Planting trees along wide avenues and streets helps reduce UHI effects by lowering surface temperatures and cooling the environment through evaporation and transpiration. In addition, it leads to an improvement in the overall air quality.

- Planting heat-resistant species along avenues and streets allows urban greening to become more adapted to urban environmental conditions and increases the effectiveness of mitigating negative UHI effects.
- The integration of urban trees, as well as bushes, perennials and similar elements within the rainwater drainage system, combined with urban cooling corridors, increases the efficiency of the UGI when it comes to UHI effects reduction.

2.3. Green roofs, green walls and urban gardens

- Roofs of buildings covered with greenery that absorbs solar radiation reduce heat influx into objects and the temperature of the immediate environment.
- Green walls refer to vertical surfaces covered with greenery that provides shading to surfaces and reduces the thermal absorption of a building, improves general air quality and reduces UHI impact.
- The establishment of urban gardens and green spaces encourages the integration of green infrastructure elements into the urban fabric, leads to positive evapotranspiration effects and reduces the accumulation of heat, which has a positive impact on the reduction of UHI effects.
- Green living fences subsume bushes, trees, climbing plants, etc. that function as separate units, and their planting positively affects the increase and transfer of temperature, provision of shade in urban spaces, as well as air quality, the general aesthetic atmosphere and the feel of a space.

2.4. Green squares and street trees

- Planting trees in existing city squares helps reduce heat absorption, expand shaded areas and improve general environmental conditions for space users.
- Planting trees along roads helps reduce UHI effects by covering surfaces, reducing surface temperatures, improving air quality and aesthetic perception of the urban environment, as well as reducing noise.

2.5. Small parks and yards

- Surfaces of small parks and yards are smaller than square, park and urban forest surfaces, resulting in a relatively low impact on the reduction of UHI effects. However, they can be efficiently used in combination with other elements of green infrastructure.
- Permeability surfaces and specific materials affecting the reduction of absorbed thermal energy can make an additional positive contribution to the mitigation of UHI effects.
- Given their size, these areas are suitable for smaller trees and shrubs of narrow, upright treetop habits, as well as climbing plants and ground covers.

2.6. Green islands along roads

- They represent belts of greenery that contain various elements of vegetation, such as grasslands, perennials, bushes, but also trees of narrower habits.
- They have a relatively small impact on the reduction of UHI effects, but with careful design and placement in space, they can cover larger areas of space, thereby reducing the amount of energy absorbed and local surface temperatures.
- By carefully selecting species, they can have a significant positive impact on the improvement of air quality, reduction of noise and light pollution.

2.7. Rain gardens

- Rain gardens are a nature-based solution for the temporary collection (and, in certain cases, filtering) of rainwater from built-up impermeable areas. They are often designed as low maintenance intensity areas and must be distinguished by a specific selection of species that can withstand both intermittent water saturation of soil and intermittent dry periods.
- Their role in water reception relieves urban drainage systems and helps reduce flood risk.
- They can cover and cool the immediate environment, as well as improve air quality by removing pollutants from plant surfaces.

2.8. Pots for planting trees and urban planting pits

- When combined with grey infrastructure elements, these pots and pits function as hybrid solutions. They also function as green infrastructure dots. and may have a permanent or temporary character.

- Their primary contribution lies in the fact that they provide shade to areas that easily absorb large amounts of heat and reduce surface temperature for the purpose of decreasing UHI effects.
- They are recommended for use only in places where planting is not possible due to the previously installed underground infrastructure. The pots and pits in which they are to be planted should have a capacity of 1250 litres max.
- Due to space limitations, we advise using these pits and pots for low trees with intensively maintained and shaped tree canopies.
- As a result of their adaptability to different spaces, they can be used to connect elements of green infrastructure into continuous shaded spaces, which has a significant impact on the improvement of quality with regard to the ecological characteristics of the space.
- Adequate integration and investment in urban planting pits can lead to a significant improvement in the growth and development conditions of urban trees. In turn, this may lead to a prolongation of the trees' life cycle, an increase in their resistance to windthrows, a reduction in the costs of their maintenance and nurturing, and a significant decrease in water losses. Nevertheless, their physiological functions will remain normal throughout their life cycle, which greatly exceeds the monetary values of implementing such urban tree planting methods.

This division represents the simplest classification of UGI elements, as well as the most prominent positive impacts on UHI effects and the most important environmental factors. These elements may, either on their own or in different combinations, form components of unique green infrastructure categories. The chosen green infrastructure should be defined with particular regard to the specificity of a given space. A positive example of conducting such a unique typology process was made when green infrastructure (GI) categories were defined in Croatia.

Table 8 Category of GI typology and a list of measures applied to GI species UHI effects mitigation

Category of green infrastructure typology	Action proposal
Park Parks are fully landscaped, open and clearly recognizable green areas that are reserved for the public needs of citizens and intended primarily for recreation. They are multifunctional spaces primarily covered by vegetation, as well as water elements, pathways, park and sports equipment, monuments, etc. Functional park design process determine the natural characteristics of the area, the intended purpose of the space, and the residents' needs. Parks in city centres are very often arranged as promenades with grassy areas that have been planted according to planned designs, most often with very few trees.	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of increasing tree canopy cover surface and the potential to maintain local biodiversity - improving habitat conditions with a view to improving water absorption rate - reducing the area of impermeable surfaces - connecting with other UGI elements for the establishment of cool and pedestrian corridors
City/urban forest City or urban forests are natural or planted forests located in an urban area; in other words, they have been integrated into or located next to the built-up space and are mostly surrounded by residential zones. They can be shaped as park areas, and when managed meaningfully, their original forest structure can remain the same. Functional-forming characteristics of city forests are determined by natural features; they consist of trees and shrub vegetation, as well as ground-level vegetation and grass. City forests can consist of separate parts for recreation with walking and cycling paths, children's	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of increasing tree canopy cover surface and the potential to maintain local biodiversity - improving habitat conditions with a view to improving water absorption rate - limiting access to vehicles with the purpose of reducing ground compaction outside the road corridors - connecting with other UGI elements for the establishment of cool and pedestrian corridors

Category of green infrastructure typology	Action proposal
playgrounds, free walking areas for pets and spaces for public events.	
Sports and recreational area These areas are usually self-contained areas that are purposefully designed and equipped for sport and recreation. They often contain elements of landscape value in their design. Sports and recreational areas include open sports fields and accompanying sports buildings. The main element in their structure must be natural green surfaces on the ground intended for various outdoor sports, e.g. football, athletics, archery, golf, equestrian sports, outdoor swimming pools, as well as for recreation with outdoor exercise equipment, playgrounds for children and young people, playgrounds and training polygons for dog, and other purposes. All outdoor spaces are completely landscaped, publicly accessible and often located near public transport stations.	- suitable areas for planting different types of trees, shrubs and perennials to expand the areas shaded by treetops and increase the maintenance of local biodiversity - possibility of using permeable surfaces - possibility of using materials with an impact on the reduction of UHI effects
Lawn Green areas whose vegetation is primarily made up of different types of grass; these areas rarely contain trees and bushes and are the result of human activity. They function as independent green areas and are the most common infrastructure form in open spaces. They form a clearly bounded space without a complex structure and are dominated by a relatively uniform texture and colour. Depending on their purpose, grasslands in urban areas can function as ornamental grasslands next to significant public buildings, residential buildings or as parts of parks, sports lawns and golf courses; this typology includes the ornamental grasslands in public areas with unrestricted public access.	- improving habitat conditions with a view to improving water absorption rate - limiting access to vehicles with the purpose of reducing ground compaction outside the road corridors
Botanical garden/ Arboretum/ ZOO Botanical gardens, arboretums and ZOOs are not classified as public parks, but are rather considered open-air museums. They function as independent green areas. and are clearly bounded by recognizable entrances. Their internal structure is complex, and is a combination of different elements, free landscape design, and a geometric approach; it also includes a number of elements of appropriate design value, equipment, as well as necessary buildings. Botanical gardens, arboretums and ZOOs play a prominent role as leisure, relaxation and strolling destination within urban fabric. Due to the very characteristics of these spaces and often their historical importance, they stand out as go-to locations for cultural events, as well as sources of inspiration for arts and numerous events. Additionally, they have a pronounced educational role.	- areas suitable for planting different types of trees, shrubs and perennials whose treetops would provide cover and the potential to maintain local biodiversity - possibility of using permeable surfaces - possibility of using materials with an impact on the reduction of UHI effects - connecting with other UGI elements for the establishment of cool and pedestrian corridors
Historical garden Historical gardens are different from regular parks and gardens in terms of artistic and creative ambition	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of

Category of green infrastructure typology	Action proposal
– Historical gardens are literally an architecture in the form of organic material. Historical garden are a highly cultivated outdoor area that is either independent or very often located next to historic buildings, castles, manor houses, churches and summer residences. Historical gardens can be built within various urban areas, including public, medical, or parochial spaces. Their design depends on the historical period in which they were established and are very often landscaped. Their composition consists of four basic elements – terrain, vegetation, water and rocks. Their grassy surfaces are primarily adorned with trees and bushes, whereas flowers take a secondary role in this regard. In addition, Historical garden contains numerous functional and aesthetic elements such as pavilions, bridges, gazebos, and water bodies, as well as defined paths and garden plastics; occasionally, they also entail decorative gardens and orchards. Historical garden are inspiring places for purposeful or recreational gatherings of residents, as well as for cultural and other events. As such, they help attain social inclusion and create a sense of belonging in the community.	increasing tree canopy cover surface and the potential to maintain local biodiversity - possibility of using permeable surfaces - possibility of using materials with an impact on the reduction of UHI effects - connecting with other UGI elements for the establishment of cool and pedestrian corridors - limiting access to vehicles with the purpose of reducing ground compaction outside the road corridors
Green constructive elements on buildings Green roofs usually have a flat surface and are less often sloping/tilted. They are covered with vegetation, with the composition of green roofs consisting of several different functional layers, drainage systems, filters, substrates and a final layer of vegetation. There is a difference between extensive green roofs, consisting mainly of resistant perennials such as succulents and drought-resistant grasses, and intense green roofs, which are more complex and made up of a combination of different plants, such as perennials, shrubs, grasses and trees, and can also be used for the cultivation of vegetables and fruits. Green walls are independent structures which are built vertically and covered with vegetation; their structure is often made out of modular tiles or other constructive frames that serve to accommodate different types of cultivation media. This, in turn, depends on the choice of vegetation dictating the forms of maintenance needs.	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of increasing tree canopy cover surface and the potential to maintain local biodiversity - possibility of using materials with an impact on the reduction of UHI effects - connecting with other UGI elements for the establishment of cool corridors
Productive green infrastructure - urban gardens, urban farms, greenhouses, public orchards Productive green infrastructures are located in urban settlements and are maintained by the inhabitants of the settlements concerned. They are either unplanned communal gardens, created on free public land as a result of informal initiatives undertaken by occupants of nearby buildings and civil society associations, or official city gardens, established following a public call addressed to cities and municipalities, allowing citizens to use the parcel	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of increasing tree canopy cover surface and the potential to maintain local biodiversity - possibility of using permeable surfaces - possibility of using materials with an impact on the reduction of UHI effects - connecting with other UGI elements for the establishment of cool and pedestrian corridors

Category of green infrastructure typology	Action proposal
either for free of or for a small annual fee. Spaces of official city gardens are clearly landscaped, with a defined division into individual row-shaped parcels that are interconnected by paths. These parcels are used for growing vegetables and fruits (berries), herbs and flowers for personal use. Other types of productive green infrastructure, such as urban farms, nurseries and public orchards, have a more pronounced economic function and represent an associated type of GI element.	- limiting access to vehicles with the purpose of reducing ground compaction outside the road corridors
Integrated urban drainage systems The most common solution for an integrated urban drainage system is a rain garden, i.e. bioretention. Such gardens are depressions covered with plants, allowing the collection of rainwater from impermeable surfaces such as roofs, pedestrian areas and paved surfaces, and activating the absorption of water into the underground. They mostly appear in trapezoidal forms with shallow depressions. There are several basic types of rain gardens in nature: classic rain gardens, rain gardens on impermeable surfaces, and rain gardens in pots. They consist of a bottom (impermeable) substrate, a drainage layer with a perforated pipe, granulation material and plants (perennials, shrubs and trees). Due to their noticeable vegetation, rain gardens can improve the visual and aesthetic perception of the city space. When in the vicinity of holiday infrastructure, rain gardens can be used for passive holidays and informal citizen gatherings.	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of increasing tree canopy cover surface and the potential to maintain local biodiversity - possibility of using permeable surfaces - possibility of using materials with an impact on the reduction of UHI effects - connecting with other UGI elements for the establishment of cool and pedestrian corridors - limiting access to vehicles with the purpose of reducing ground compaction outside the road corridors
Urban wetland Urban wetlands are shallow depressions densely covered with plants and located within or around urban areas. They can be natural or artificial. Artificially built wetland systems are functionally designed for the purification of rainwater and permanent retention of a certain volume of water, consisting of several sections of different depth, usually up to six meters. They are designed to imitate natural wetland systems and are often the dominant element in space dimension-wise. Wetland systems play a significant role in reducing the occurrence of urban floods and droughts, purifying rainwater, adapting to climate change, as well as reducing the impact of urban heat islands and soil erosion. They can also be used as a place for rest and recreation and other educational activities harmoniously linked to spending time in nature.	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of increasing tree canopy cover surface and the potential to maintain local biodiversity - possibility of using permeable surfaces - connecting with other UGI elements for the establishment of cool corridors
Park cemetery Cemeteries are enclosed areas of land with burial plots, communal infrastructure and accompanying buildings. They are classified as communal buildings owned by the city or municipality in which they are located. Due to their park-like features, some cemeteries have been	- areas suitable for different types of trees, shrubs and perennials, allowing for a simple increase in the tree canopy cover surface and the potential to maintain local biodiversity - possibility of using permeable surfaces

Category of green infrastructure typology	Action proposal
declared monuments of park architecture. Park cemeteries and cemeteries with both park-like and architectural landmarks that stand out as components of green infrastructure. Park cemeteries contain grass elements with straight rows of trees; they have an orthogonally shaped plan with properly arranged burial plots. In the coastal part of Croatia, park cemeteries are also characterised by rows of chapels. Architectural cemeteries are characterised by buildings of different types and shapes, and are most often bounded by porches.	- possibility of using materials with an impact on the reduction of UHI effects - connecting with other UGI elements for the establishment of cool and pedestrian corridors
Brownfield area Brownfield area are former industrial and military complexes, larger complexes of other purposes, or undeveloped surfaces, which have lost their basic function over the years. When it comes to urban renewal, these areas are of great importance as they are very often located within the very core of urban centres. Such surfaces can have two potential functions, i.e. be used as either temporary or permanent green infrastructure. Each Brownfield land needs to have a defined method of use. This method should be selected in accordance with the inventory of vegetation created by natural succession and the significance of the existing condition in the context of wider green infrastructure development. Brownfield lands are characterised by a closed structure, often bounded from surrounding area, and visually protected, with a limited access. Their design needs to be adapted to the needs of new users and to the infrastructure of the previous purpose.	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of increasing tree canopy cover surface and the potential to maintain local biodiversity - possibility of using permeable surfaces - possibility of using materials with an impact on the reduction of UHI effects - connecting with other UGI elements for the establishment of cool and pedestrian corridors - limiting access to vehicles with the purpose of reducing ground compaction outside the road corridors
Watercourse, wetland, riparian zone and surface inland waters Watercourses include water zones and all publicly accessible coastal areas with a predominant proportion of natural elements. They are characterised by a line shape and, as a rule, have anti-flood and other water management measures in place. There are several types of watercourses in construction areas: rivers, streams, ephemeral streams, diversion channels, navigation channels, irrigation canals, lakes and ponds, which, together with rain gardens, form the urban water system network. Inundation areas have a great potential for rainwater management and for the development of recreation and outdoor living areas. Additionally, they are safe havens for plant and animal species living in wetlands.	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of increasing tree canopy cover surface and the potential to maintain local biodiversity - possibility of using permeable surfaces - connecting with other UGI elements for the establishment of cool corridors
Square Squares are open city spaces completely or partially bounded by buildings or streets. They can be entirely paved and without green areas, with their size depending on their location and purpose, ranging from small urban plateaus to large city squares. When it comes to green infrastructure, if they contain	- suitable areas for different types of trees, in particular the use of urban planting pits - possibility of using permeable surfaces - possibility of using materials with an impact on the reduction of UHI effects - connecting with other UGI elements for the establishment of cool and pedestrian corridors

Category of green infrastructure typology	Action proposal
elements of greenery and water, squares can significantly contribute to the creation of an environmentally sustainable city, having a positive impact on air quality, as well as on noise and stress reduction. Additionally, they can contribute to a general feeling of comfort for people spending time outdoors. In city squares, vegetation should be resistant to specific rainfall conditions, soil compactness and maintenance requirements.	- limiting access to vehicles with the purpose of reducing ground compaction outside the road corridors
Sea coast Anthropogenic seashore forms include ports, marinas, watercourses and docks, coastal roads, city beaches and beaches along tourist complexes; the seashore category also includes waterfronts as the most frequent gathering destination for residents. This typology also includes city coasts, promenades and beaches. When green infrastructure is planned, cities located along the sea coast should make sure that their coastal area is protected environmentally, as well as that the specific identity of their location is preserved. The design of a city coast and beach depends on the primary function of the space, the existing level of built-up, and the environmental and spatial management measures defined.	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of increasing tree canopy cover surface and the potential to maintain local biodiversity - possibility of using materials with an impact on the reduction of UHI effects - connecting with other UGI elements for the establishment of cool and pedestrian corridors
Touristic zones Touristic zones are areas that are intended exclusively for tourism through spatial planning, i.e. hotel complexes, campsites, as well as sea or other coastlines along water surfaces belonging to them. Green infrastructure elements within tourism zones have multiple benefits. In addition to promoting biodiversity, UHI and microclimate change mitigation, these zones are beneficial for the health of their users as they provide leisure, pleasant views, and the possibility to spend time outdoor in air and sunshine. Additionally, they often function as an incentive for physical activity. Outdoor recreational facilities should be made available to the local population throughout the year.	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of increasing tree canopy cover surface and the potential to maintain local biodiversity - possibility of using permeable surfaces - possibility of using materials with an impact on the reduction of UHI effects - connecting with other UGI elements for the establishment of cool and pedestrian corridors - limiting access to vehicles with the purpose of reducing ground compaction outside the road corridors
Green areas next to residential buildings Private gardens adjacent to family houses, public and semi-public open spaces (within residential settlements and between multi-residential buildings) can significantly contribute to the functions and well-being of green infrastructure, and, when shaped properly, can form urban corridors. In spatial plans, the conditions for the construction of residential areas insufficiently define the guidelines for the arrangement and functions that the independent part of a building plot should accomplish. Nevertheless, these spaces are often oases in which people spend most of their everyday life, with which they identify, and which are of particular importance when it comes to increasing life quality. At the same	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of increasing tree canopy cover surface and the potential to maintain local biodiversity - possibility of using permeable surfaces - possibility of using materials with an impact on the reduction of UHI effects - connecting with other UGI elements for the establishment of cool corridors

Category of green infrastructure typology	Action proposal
time, it is very clear that there is a lack of such green areas in everyday life and that these areas are designed without the necessary standards of green infrastructure.	
Green areas next to public, social and economic buildings When it comes to green infrastructure, open areas alongside public institutions, health institutions, nursing homes, educational institutions, kindergartens, campuses, shopping and business centres and buildings in economic zones are an important element of sustainable urban development and the formation of green infrastructure corridors. In spatial plans, the conditions for the construction of areas of public, social and economic use insufficiently define the guidelines for the arrangement and functions that the free part of building plots should achieve, so it is necessary to pay additional attention to their design and the creation of continuous green spaces. In addition to the quality of the ambiance they create and their visual quality, green areas play a significant role in the improvement of microclimatic conditions and in the possibility that a part of the activities related to their basic use takes place in the open space.	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of increasing tree canopy cover surface and the potential to maintain local biodiversity - possibility of using permeable surfaces - possibility of using materials with an impact on the reduction of UHI effects - connecting with other UGI elements for the establishment of cool corridors - limiting access to vehicles with the purpose of reducing ground compaction outside the road corridors
Theme park Theme parks are generally single-function spaces whose activities, equipment and overall structure are guided by one recognizable topic or concept. Theme parks in the Mediterranean can, thus, have a sea or tropical theme, parks in mountainous areas may focus on the topic of research or adventure, and areas with numerous water bodies can put an emphasis on the theme of water sports or exploration of aquatic flora and fauna. Theme parks are structurally and aesthetically landscaped, they must be adapted to the climatic characteristics of the area, and must provide protection against all adverse weather conditions and changes. Their role in urban areas is often cultural, scientific, educational, recreational, entertainment-related and aesthetic. They have a permanent character and offer accommodation capacities and gastronomic facilities that allow visitors to stay for a longer time.	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of increasing tree canopy cover surface and the potential to maintain local biodiversity - possibility of using permeable surfaces - possibility of using materials with an impact on the reduction of UHI effects - connecting with other UGI elements for the establishment of cool corridors - limiting access to vehicles with the purpose of reducing ground compaction outside the road corridors
Archaeological park Archaeological parks are a type of landscape that testify to the long-standing presence of humans in an area. They have an artistic, historical and anthropological value and are often registered cultural objects. They may take the form of a grassland or a meadow with sparse vegetation and archaeological remains, building complexes or assemblies, or zones with linear outlines of structures	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of increasing tree canopy cover surface and the potential to maintain local biodiversity - possibility of using permeable surfaces - possibility of using materials with an impact on the reduction of UHI effects - connecting with other UGI elements for the establishment of cool and pedestrian corridors

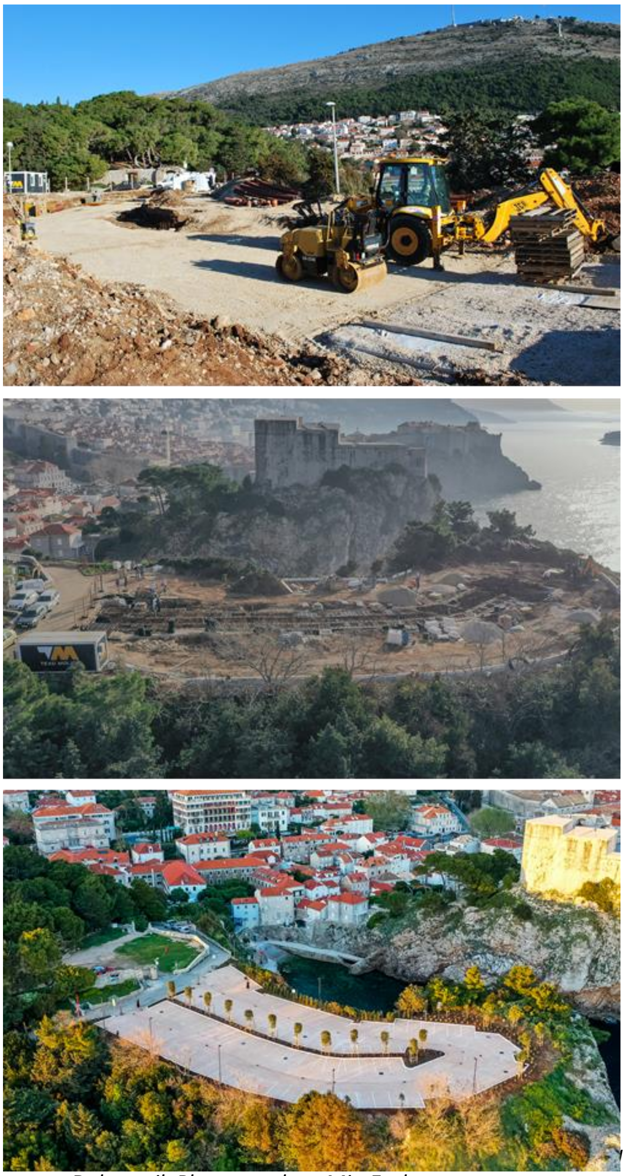
Category of green infrastructure typology	Action proposal
or scattered spatial elements. They can also be located within narrow urban matrices. Depending on the degree of research conducted and the protection measures defined for a given site, by decorating, presenting and promoting an archaeological park, it can be valorised appropriately. Moreover, by adding attractive cultural, tourist-focused and educational facilities, the number of visitors in the park can be increased, leading to the creation of an attractive space for an interrelation between tradition, environment and humans.	
Green traffic corridors Transport corridors are linear infrastructure structures defined in spatial plans. They consist of a traffic area and accompanying structural facilities such as footpaths, bicycle lanes, and parking areas. However, each of these elements can also appear as individual traffic areas, especially in narrow city circuits and centres. When it comes to green infrastructure, supporting elements such as green areas, lines of trees, narrow grasslands, as well as areas with low and high vegetation, play an important role. Such protective greenery functions as a buffer between the pavement and the rest of the built-up space, directs the panoramic view, blocks the noise, provides protection from dust, glare and gusts of wind, and reduces the heating intensity of paved and asphalted surfaces. In addition, creating smaller spaces between trees can lead to reduced driving speed and better road safety, whereas planting more greenery within the frames of transport corridors reduces the exposition to urban flooding and helps keep rainwater off the roads.	- areas suitable for planting different types of trees, shrubs and perennials with the purpose of increasing tree canopy cover surface and the potential to maintain local biodiversity - possibility of using permeable surfaces - connecting with other UGI elements for the establishment of cool and pedestrian corridors - limiting access to vehicles with the purpose of reducing ground compaction outside the road corridors
Planting trees The typology refers to individual trees that will be planted by 2030 within all other typologies listed in the manual. This typology allows for a horizontal approach. Individual planting in public and private spaces will be registered, regardless of how they are planted (selectively, in straight lines, etc.). All tree planting processes, organised on the basis of various initiatives by the local self-government, civil society associations, as well as other institutions and organisations that have defined reducing CO2 emissions and increasing the quality of life in the local community as their strategic goal, will be registered.	- connecting with other UGI elements for the establishment of cool and pedestrian corridors - limiting access to vehicles with the purpose of reducing ground compaction outside the road corridors - provide sufficient space for the parts of three aboveground, and even more so below ground. Minimum recommended volume of uncompacted soil

INCORPORATING TREES AND PLANTS IN THE BUILT ENVIRONMENT

During their phylogenetic development, plants adapted to specific habitat niches occupying space in cohabitation with other living beings. When integrating plants into the urban space, in addition to aesthetic appearance and physical placement in space, it is necessary to look at the habitat conditions into which plants should fit, as well as the specific relationships that can result from the interaction of other living beings and people living in the said space. When species for planting are selected, special attention is paid to soil analysis and the amount of space available as, depending on the species, half of each plant's organism is found and developed in the soil and is adapted to certain conditions.

Given that the space for root development in the soil is often very limited, various methods allowing uninterrupted root development (Figure 17), as well as limiting and preventing negative root interactions with underground infrastructure, have been developed. When it comes to other uses of this planting method, among the most important ones is the adequate volume of uncompacted soil which enables the development of healthy and resistant trees, an almost unlimited access to vehicles (with a bearing capacity of minimum 25 t/m^2), an increase in the trees' resistance to windthrows, the creation of temporary zones for precipitation collection, etc.

In the context of UHI mitigation adaptation measures, it is possible to use tree canopies to almost completely cover the areas that are traditionally a major source of solar radiation absorption, such as large car parks around shopping malls, without losing parking spaces, and reducing the number of SUHIs.



space, Dubrovnik Photos author: Mia Erak

It is important to emphasise there is a need for adequate individual dimensioning of the volume of uncompacted soil for root development, which is done in accordance with the dimensions of adult trees' treetops. However, in principle, it is recommended to provide large trees (25-30 m tall) with 35-40 m^3 of soil, medium-sized trees (15-25 m tall) with 18-35 m^3 of soil, and small trees (4-15 m tall) with 10-18 m^3 of soil. This greatly exceeds the current capacities, and is negatively manifested by the degraded physiological condition of our urban tree population and reduced areas covered by tree canopies.

Given the projections of changing climate conditions, especially in the season of above-ground tree parts growth, when it comes to the choice of urban tree species, special attention should be given to species which are to be planted along the streets and other spaces with a high proportion of impermeable surfaces. Such trees must be specially adapted to growth in arid conditions and exposure to intense solar radiation. Since these are intensively used areas, it is recommended to choose species that are more resistant to the negative impact of mechanical loads by wind bursts and that can be further enhanced by an urban canyon effect. By respecting these features, it is necessary to leave the domain of selecting strictly native and domesticated species and look for suitable species in the environment. Given the very diverse microclimatic conditions, there can be significant complications if several species are singled out, so using a multidisciplinary approach to the development of projects focused on integrating greenery into urban spaces by employing both landscape architects and experts in the field of urban forestry and arboriculture is recommended. When choosing climate-adapted and biomechanically suitable new species, upon researching the potential specie's invasiveness in the new environment and its compatibility with the existing flora and fauna in it, as well as before mass planting, it is recommended to conduct monitoring tests to assess the suitability of the given species in the area.

Some of the species that should be assessed include species which have been specially selected for urban habitats, such as the *Ulmus ©resista* 'New Horizon' and other resistant elm cultivars, as well as the species *Alnus x sphaetii, Quercus texana* 'New Madrid', *Zelkova serrata* 'Green Vase', *Gleditsia triachanthos* 'Skyline', *Acer rubrum cvs.*, *Pyrus calleriana* 'Aristocrat', P*arotia persica, Jacaranda mimosifolia*, *Nyssa sylvatica, Fagus orientalis* 'Iskander', *Platanus orientalis* 'Minaret' and similar. When it comes to indigenous species, plants such as *Acer campestre cvs., Acer monspessulanum, Quercus frainetto, Celtis australis* (warmer continental part of the Republic of Croatia), *Cercis siliquastrum, Corylus collurna, Fraxinus ornus, Vitex agnus-castus, Quercus coccifera* and the like should be considered.

In addition to conducting an appropriate selection process, it is important to ensure that the quality of the work execution has also been conducted and monitored. Apart from choosing a specie, the biggest challenge currently is the quality control of the planting material delivered, as low quality planting material significantly impairs the positive effects of planting and reduces the efficiency in the interaction between trees and the environment by reducing the tree canopy cover surface. This is mostly negatively affected by high mortality and a significantly prolonged period of new trees' adaptation to the new habitat. An additional negative effect leading to a decrease in the efficiency of the reduction of UHI negative effects is caused by tree topping, i.e. the removal of all thinner branches with leaves. It is recommended to explore the possibilities of defining legal frameworks, aiming to prohibit the given procedure. The only exception in this regard should be cases where topping is prescribed as a form of sanitation based on advanced biomechanical diagnostic tree control methods or as part of the maintenance of special growing habit canopy forms. For the purpose of long-term protection of covered areas, there should also be compensations for the excessive loss of such areas due to aggressive and unprofessional tree-care operations, with the exception of abovementioned cases.

Given the climate challenges, integrating GI into various spaces through nature-based solutions is becoming evermore important in spatial planning processes. Such a practice requires increasingly intensive research, development and standardization of methodologies for UHI effects mitigation. Initiatives dealing with UGI integration are gaining importance in public perception due to a series of positive effects both on the urban space and on the people who live in the city.

One such standardisation is the so-called "3-30-300" rule, which imposes that one should have a view of three visible trees from the vicinity of their home, workplace or place of study, at least 30% of tree canopy cover and a residence no more than 300 m away from a large and well planned public green space. This rule was presented by Cecil Konijnendijk, who thereby laid the foundations for the integration of green infrastructure in urban spaces, emphasising the importance of tree visibility, tree canopy cover and easy and fast access to public green spaces within 300 meters. This rule has been adopted in various cities around the world and has been supported by international organisations. Its aim is to promote equal access to nature for mental and physical well-being and adaptation to climatic conditions, as well as to improve urban living standards in general.

BLUE INFRASTRUCTURE

As a measure of UHI negative effects mitigation, blue infrastructure can be combined with green infrastructure. This creates nature-based solutions that, in addition to mitigating UHI effects, support simple and complex relationships between the elements of green and blue infrastructure and cohabitant organisms that are an essential part of nature development. Blue infrastructure elements are most effective when they act in synergy, increasing evaporative cooling, improving natural water cycles and including vegetation such as trees, shrubs, perennials and others, which mitigate heat accumulation in urban environments.

Their efficiency is primarily determined by cooling mechanisms that exhibit daily and seasonal variability and depend on background climatic conditions and characteristics of surrounding urbanised areas. The combination of blue and green infrastructure elements and their interconnection increases UHI mitigation potential.

The basic elements of blue infrastructure are:

natural (rivers, lakes, etc.) **and artificial bodies of water** (artificial lakes, reservoirs, etc.). Artificial bodies of water have been created to meet specific spatial needs and represent an important part of blue infrastructure. They can be used for water storage, flood control, recreational purposes, as well as for UHI effects mitigation in following ways:

- by acting as heat reservoirs absorbing excess heat during the day; stored heat is then slowly released throughout the night, soothing temperatures in the surrounding areas
- evaporation of bodies of water provides a cooling effect, further reducing temperatures because part of the sun's radiation is not used to heat the space but to stimulate water evaporation from the water surface.

Guiding principles aimed at the reduction of UHI effects:

- consideration of restoration of river watercourses, as well as maintenance of vegetation along the watercourses
- consideration of closed stream reactivation through the removal of impermeable materials
- landscape design of watercourses as part of cool corridors network.

Wetlands and floodplains form an ecosystem characterised by water-saturated soils and specifically adapted plants. Wetlands and floodplains act as natural sponges (buffer zones) and are characterised by a great ability to absorb rainwater. Additionally, they have an effect on the reduction of UHIs in the following forms:

- they act as natural absorption surfaces for of large amounts of water, absorbing rainwater from impermeable surfaces, and thus taking some of the heat from the paved surfaces
- evapotranspiration from swamp vegetation helps cool of the ambient air; part of the solar radiation emitted is not used to heat the space, but to stimulate the evaporation of water from the soil and the plant.

Guiding principles aimed at the reduction of negative UHI effects:

- design of water elements in existing public spaces surrounded by vegetation adapted for growth in a saturated water habitat
- arrangement of new public green areas with water elements and plants that are adapted to life in a saturated water habitat (hydrophilic vegetation).

Channels designed to transfer water for cooling purposes, such as industrial processes or energy production, also have an impact on reducing UHI effects in the following forms:

- they facilitate the transfer of water for cooling purposes and form airflow corridors; water flow through channels helps dissipate heat generated by industrial activities
- evapotranspiration from wetland vegetation also helps cool the ambient and further reduce temperatures by inducing water vapour to reflect a part of the solar radiation emitted.

Rainwater treatment and drainage systems consist of infrastructure for rainwater drainage from impermeable surfaces (e.g. roads, roofs, parking lots, etc.). The means of UHI effects reduction related to this type of infrastructure include:

- reception and drainage of rainwater from impermeable surfaces
- drainage of heated water, which helps transfer thermal energy from the area of built-up surfaces to the area with cooler natural surfaces
- stimulation of infiltration and evapotranspiration, which reflect part of the thermal energy
- use of smaller green infrastructure elements within rainwater treatment systems such as rain gardens, which improve cooling through evaporation and transpiration due to physiological activities of plants.

Guiding principles aimed at the mitigation of UHI effects:

- integration of sustainable rainwater drainage systems into the existing grassland strips of various street networks
- planning and development of sustainable rainwater drainage systems during new road planning processes
- development of design elements for temporary water retention for the purpose of cooling areas characterised by extreme temperatures after extreme rainfalls in the summer months (e.g. rain gardens or retention for temporary swamping).

Blue roofs are spaces built with the aim of controlling rainwater drainage. They can be pond-shaped or integrated into the green roofing system. Blue roofs can help reduce UHI effects because:

- the temporary retention of water on the roof surface helps provide cooling through evaporation and transfer of a part of heat energy
- they provide insulation and further contribute to the reduction of surface temperatures on the basis of evapotranspiration through the physiological functions of the embedded green infrastructure that can be an integrated part of the infrastructure in question.

Guiding principles aimed at reducing the negative UHI effects:

- encouraging the development of water elements within green roofs (e.g. micro ponds, fountains or smart irrigation systems).

SPACE PLANNING METHODS WHICH MITIGATE URBAN HEAT ISLANDS

1.1. Building morphology and orientation play a key role in the mitigation of UHI effects, in particular through measures such as building layout and orientation optimisation, as well as the improvement in natural air flow. A careful arrangement of buildings (1.1.1.) enables the construction of corridors for the circulation of cooler air, allowing heat trapped inside the city to be dispersed. In addition, designing buildings so as to make them maximally exposed to the direction of prevailing winds supports natural cooling and ventilation processes. Together, these measures reduce reliance on energy-intensive cooling systems.

1.1.1. Morphology

The morphology of the city, including the construction density, the height of buildings and GI, is extremely important in mitigating the effects of UHIs.[100,101] Low and high values of the Sky View Factor in combination with tall urban trees may help reduce UHI intensity.[102] Additionally, by broadening one's understanding of urban morphology and heat dispersion, we can reduce the impact of anthropogenic heat load on air temperature.[103] However, depending on the local microclimate and urban geometry, the efficiency of specific mitigation strategies, such as green or cold roofs, may vary.[104]

1.1.2. Orientation

The orientation of buildings also plays an important role in alleviating UHI effects, as it influences airflows and reduces surface temperatures. That way, it can also have an effect on optimal thermal comfort from the pedestrian perspective.[105,106] Also, a significant level of mitigation of negative UHI effects, as well as the reduction of radiation from the eastern and western building facades, can be achieved by using cold materials, which has a very favourable effect on the microclimate of the space.[107] With the demonstrated positive effects in mind, in his research, Loh goes a step further and suggests certain solutions to changing climate conditions based on specific design and development for the purpose of improving the morphology of buildings and facades in a way that minimises the negative UHI effects.[108]

1.2. Open spaces

Open spaces are very important in the context of mitigation of UHI effects, with the role of space cooling generated by tree canopy cover and the potential of urban gardens to reduce the effects of UHIs especially emphasized. [109,110] The use of land and open spaces[111], as well as the methodology of planning open spaces,[112] also have a significant impact on cooling, as they exploit natural temperature gradients.

1.2.1 Urban canyons

Urban canyons, areas with high-rise buildings and narrow streets, play a key role in the mitigation of UHI effects. Innovative cold materials, such as those with high albedo (ratio of light reflected from a surface and light absorbed by a surface, usually expressed as a percentage), can be applied to building surfaces with the purpose of reducing additional space heating and decelerating the deterioration of the local microclimate.[113] Facades with reflective features, especially white cold diffuse materials, can also significantly reduce temperatures within urban

[102] Liu, 2023
[103] Yuan, 2021
[104] Ambrosini, 2014
[105] Hong, 2015
[106] Taleghani, 2021
[107] Rosso, 2015
[108] Loh, 2021
[109] Szkordilisz, 2014
[110] Humaida, 2023
[111] Fowler, 2009
[112] Irie, 2006
[113] Rosso, 2018

canyons.[114] Green roofs and walls further reduce temperatures by decreasing the rate of the absorption of energy from solar radiation and increasing the feeling of comfort in a space by means of water heat transfer.[115] Optimisation of air flow and strategic location of tall buildings in space further reduces air temperature in urban canyons.[116]

1.2.2. Street profiles

Research has shown that street profiles are also important in the mitigation of UHI effects. Urban warming mitigation strategies, such as the implementation of new technologies and surface materials that absorb less solar radiation (cold surfaces), including reflective surfaces and installation of solar collectors, have proven to be effective in reducing surface temperatures.[117] The development of green infrastructure and the use of shading elements, such as pergolas, canopies and solar panels, can help alleviate negative warming factors.[118] These strategies, when integrated into street profiles, can help reduce the overall impact of UHIs in urban spaces.

1.2.3. Parking spaces and car parks

Parking spaces and car parks also play an important role in mitigating UHI effects on the basis of various interactions and impacts. Converting asphalt-covered parking spaces into grass-covered parking spaces can reduce surface temperatures and heat circulation.[119][120] Furthermore, increasing parking lot albedos can significantly reduce air temperature and improve thermal comfort for pedestrians[121]. Finally, the integration of radiating reflective road surfaces with elements of green infrastructure has proven to be a significant step toward the reduction of air and surface temperature.[122]

1.3. Urban equipment and materials play an important role in mitigating UHI effects by offering different measures to counteract its effects. Shading structures and elements provide shelter from direct sunlight, reducing surface temperatures and alleviating overheating and heat stress. Cooling benches consist of materials with high thermal conductivity or cooling mechanisms that aim to provide comfortable seats, dispersing the heat of the seated surfaces. In addition, water elements, such as fountains or ponds, contribute to cooling by evaporation. Due to their ability to reduce heat absorption and retention, materials and paints can significantly contribute to reducing the effects of UHIs. Using materials with a high albedo helps lower surface temperatures and alleviate the retention of thermal energy. Similarly, using paving materials designed to reflect heat rather than absorb it can further reduce the UHI effects. Such mitigation strategies not only contribute to the creation of cooler urban spaces, but also reduce the demand for cooling energy, promoting sustainability and resilience in urban environments.

1.3.1 Urban equipment, fountains and water elements

Research has shown that elements of urban equipment, such as fountains and other water elements, can help mitigate the effects of UHIs. As Steeneveld[123] concluded in his research, Although water bodies can slightly increase the daily maximum UHI, water features such as fountains and canals have proven to be a means of reducing heat and increasing thermal comfort in urban areas[124]. The integration of wetlands into the construction of city districts has also proven to lead to a decrease in surface and air temperatures.[125] These studies suggest that the presence of water elements in urban areas can play a significant role in the mitigation of undesirable UHI effects.

---

[114] Morini, 2018
[115] Djedjig, 2015
[116] Priyadarsini, 2008
[117] Xu, 2021; Cheela, 2021
[118] Bozonnet, 2015; Peluso 2022
[119] Onishi, 2010
[120] Takebayashi, 2009
[121] Sen, 2020
[122] Peluso, 2022
[123] Steeneveld, 2014
[124] Moosavi, 2017
[125] Ruiz-Aviles, 2020

1.3.2. Materials and colours

Various materials and colours can also be used for the purpose of UHI mitigation. The cooling potential of natural materials with high thermal resistance, such as bamboo and compacted soil, stands out as particularly useful in construction this regard.[126] The development of cold and super cool materials, including those of low surface temperatures, with the purpose of urban heat absorption minimisation, is also an important step forward in the minimisation of negative UHI effects.[127] Materials with high albedo, low heat absorption potential and low thermal energy storage capacity used for pavements and roofing play a significant role in the reduction of surface temperature of built-up areas[128][129].

In addition, the albedo effect is a phenomenon that represents the proportion of sunlight diffusely reflected from the surface. It is measured on a scale of 0 (corresponding to a black body absorbing all radiation) to 1 (corresponding to a body reflecting all radiation). White surfaces, such as snow hills, have a high albedo time and a relatively low temperature because most of the sunlight that falls on the surface is reflected from the surface of the soil, while dark surfaces such as asphalt have a low albedo and a relatively high temperature.

[126] Kandya, 2018
[127] Santamouris, 2020
[128] Pratiwi, 2018
[129] Radhi, 2014

TECHNOLOGICAL MEASURES

In order to reduce the negative effects of urban warming, research and development of new technologies that can be implemented in the urban environment have been initiated. These technologies are divided in accordance with their interaction with negative factors and their mode of cooling.

The following are descriptions of energy saving measures by type of technology:

1. Photovoltaic systems convert sunlight into electricity using solar cells. In the context of UHI effects, they can be implemented to mitigate the effects of existing UHIs, but also to prevent the emergence of new ones. By including photovoltaic systems in urban infrastructure, cities can save on the energy needed for heating. Furthermore, they can help improve energy resilience of urban areas as they decentralise energy supply and reduce the baseload on centralised networks during peak times.

- The installation of photovoltaic systems with the purpose of producing clean, renewable energy reduces dependence on fossil fuels and the amount of heat emissions generated by conventional energy production systems.
- The integration of photovoltaic systems into buildings enables surfaces to receive cover and decrease solar heat load, which helps lower the temperatures in the interior of buildings.
- With the exception of the buildings sector, solar panels can also be used in open spaces, such as public transport stops or as part of urban equipment (shade structures, benches, etc.), which at the same time provides protection from solar radiation and to energy production.

2. Highly reflective coatings are specially formulated to reflect sunlight instead of absorbing it. Applied to surfaces such as roofs and pavements, such coatings reduce the amount of solar radiation absorbed by buildings and other urban infrastructure, resulting in a decrease in surface temperatures. This helps mitigate the effects of UHIs as it prevents heat accumulation. Furthermore, they are a source of energy savings, but also of financial savings, as they reduce the need for air conditioning and cooling systems. In addition, highly reflective coatings can contribute to the improvement of air quality by reducing the formation of ozone in the soil (as a by-product of the physical interaction of sunlight and air pollutants).

3. Thermal insulation technologies are designed to minimise heat transfer between the interior and the exterior of buildings, thus reducing the need for heating and cooling. In urban environments, where buildings are densely clustered, effective insulation is essential for the mitigation of UHI effects. Such isolation can be achieved through energy renovation of buildings, given that strengthening the protective envelope of buildings functions as an energy efficiency measure.[130] By improving the thermal performance of buildings, insulation reduces the amount of heat absorbed and helps to maintain more comfortable temperatures in the interior. Common insulation materials include fibreglass, foam and reflective foil, which are placed in walls, roofs and floors to create a barrier against heat flow. In addition, innovative insulation technologies, such as aerogel and vacuum insulation panels, offer higher levels of thermal resistance in thinner profiles, allowing more efficient use of space. In the context of nearly zero-energy buildings, the optimal thickness of thermal insulation is 16 cm for continental and 8 cm for coastal Croatia. It is also important to emphasise the impact of building design on the efficiency of thermal protection (more compact buildings have greater energy savings), the influence of the type of glazing, as well as the possibility of using devices for protection against solar radiation (devices on the inward-facing part of glass or between glass layers, devices on the outside, loggias, eaves, marquees, etc.).[131]

4. Cooling technologies cover a range of strategies and systems aimed at reducing temperatures in the urban environment. When it comes to the mitigation of UHI effects, cooling technologies play a key role in the reduction of heat absorption caused by urbanisation and human activities. Passive cooling strategies use natural phenomena such as wind and thermal physical factors to stimulate air flow and to move and disperse heat generated by activities from the building and transport sectors. On the other hand, active cooling systems rely on mechanical or technological temperature reduction methods, such as cooling cycles or spraying systems. By combining passive and active cooling approaches, it is possible to improve the resilience and quality of space in cities, while

[130] Energy Efficiency Act, OG No. 127/14, 116/18, 25/20, 41/21
[131] Ministry of Physical Planning, Construction and State Assets, 2019

reducing energy consumption and negative environmental impacts. In this context, it is important to develop efficient cooling systems in the building sector, i.e. systems that measurably reduce the primary energy consumption needed to supply one unit of delivered energy within the relevant system boundary in a cost-effective manner, in accordance with the cost-benefit analysis and the law governing the heat market, and taking into account the energy needed for extraction, conversion, transport and distribution.[128] It is also important to emphasise the need for the construction of nearly zero-energy buildings combining the use of renewable energy sources and energy efficiency measures, including efficient space cooling. In the building sector, the energy required for cooling depends on the climatic conditions at the location of the building, the architectural-construction characteristics of the building, the method of ventilation (natural or mechanical) and the purpose of the building (family house, multi-residential building, office building, educational building, store building, hotel and restaurant, hospital, sports hall, other non-residential buildings).[129] With all this in mind, it is possible to apply measures related to the improvement of architectural-construction characteristics, i.e. to design and build buildings with high-quality envelopes, to adapt the shape of the building to the climate context and the environment in which it is located, and to take into account the orientation of the openings in accordance with the cardinal directions and the exposure to solar radiation.

5. Solar ventilation systems use solar energy to power fans or ventilation vents that circulate air to remove heat from buildings. By harnessing renewable energy, these systems reduce dependence on conventional energy sources and help mitigate UHI effects. Solar ventilation systems can be particularly effective in hot climates where cooling needs are high and the amount of sunlight abundant. By integrating solar ventilation systems into the design of buildings, cities can improve air quality, increase user comfort and reduce energy costs used by classical space cooling methods. In addition, these systems can contribute to the overall sustainability of urban infrastructure by reducing carbon emissions and dependence on non-renewable resources. Furthermore, solar ventilation systems can be combined with other passive cooling strategies, such as natural ventilation and space shading, for the purpose of cooling efficiency maximisation. In conclusion, solar ventilation systems offer a cost-effective and environmentally friendly solution to the mitigation of UHI effects and for the promotion of sustainable urban development.

CONCLUSION – MEASURE IMPLEMENTATION

In order to mitigate the effects of UHIs, it is important to implement measures into spatial planning and construction processes and to use available instruments that enable a comprehensive approach to the mitigation of negative consequences. When creating spatial plans (or their amendments), it is necessary to adapt their purpose to the climatic context and to define the measures for the most critical parts of the settlement in the rules of implementation, namely those where the existence of UHIs has been determined by identification. When new interventions are planned, it is also important to take into account the spatial characteristics that contribute to the creation of UHI effects and to try to prevent them. These may refer to:

- the morphology and orientation of buildings and their interrelationship for the purpose of forming cool corridors, which can be defined on the basis of the location of the building, construction of the building plot, building coefficient, height, and the number of floors
- a more detailed prescription of the typology, proportion and shape of buildings in the context of thermal insulation efficiency
- the use of highly energy-efficient materials, as well as colours and materials which help reduce the effects of UHIs and can be defined within the frames of the requirements for the development of buildings, i.e. prescribing the required building materials and their properties
- the implementation of nature-based solutions (e.g. green roofs and facades) in parts of settlements with higher construction density through defining the conditions of building design
- an increase in the share of green spaces and tree canopy cover on the basis of conditions prescribing the regulation of the scope of interventions in the area (defining the share of natural terrain that can affect the creation of a pleasant microclimate)
- the development of diverse public green spaces and their interconnection with the green infrastructure system through the provision of specific measures for areas of special constraints;
- integral reflection on and implementation of UHI mitigation measures in areas suitable for comprehensive renovation by prescribing measures for urban renovation and transformation.

In addition to the spatial plans themselves, when it comes to the mitigation of the negative impacts of UHIs and the achievement of climate resilience by urban areas, other available instruments and tools must be mentioned, including:

- Green Urban Renovation Strategies (GURS) as a strategic basis that, among other things, aims to help urban areas adapt to climate change and strengthen resilience to risks. It is important to include the results of UHI identification and mapping in the analytical part of the URBS Strategy and, based on the results, to define measures and projects whose integration into spatial plans and direct implementation will ensure favourable microclimatic conditions for residents.
- Demographic projections, forecasts and analyses (expert studies).
- Modelling scenarios for the prediction of climate change impacts; tools for modelling (overheating, noise, and air quality, etc.)
- Instruments for public engagement and participatory management of urban spaces (workshops, focus groups, survey questionnaires and research).
- Economic instruments (providing co-financing to projects under the Operational Programme Competitiveness and Cohesion 2021– 2027, National Recovery and Resilience Plan, etc.).
- Project management tools (for the coordination of multiple projects and the integrity of individual projects).
- Education, continuous professional development and dissemination of awareness (for administrators, decision-makers and the general public).

Green and blue infrastructure in correlation with the environment has proven to mitigate the negative effects of UHI. Given the relative size of the embedded elements, this infrastructure can have a negligible effect, but by increasing the area of space influenced by green and blue infrastructure, it is possible to produce a significant positive impact on the surrounding area, as confirmed by many studies. With the implementation of examples of positive practice, it is possible to synergistically enhance the cooling effects in urban spaces within the frames of urban planning processes. The evaluation of the use of space, the use of information related to the typology of green infrastructure and the development of special legal and regulatory frameworks that enable the long-term preservation and stability of the elements of green infrastructure play an important role in that synergistic approach.

Mitigating the impacts of UHIs in cities requires a comprehensive approach involving different urban elements, open spaces, urban equipment and materials, green infrastructure and technology. The design and orientation of the construction of urban areas is extremely important when it comes to controlling air flow and exposure to sunlight. This is particularly pronounced in narrow streets with an adequate location of buildings that facilitates airflow and minimises heat retention. Open spaces, such as urban canyons, can be adapted for better air flow and shading, and large shopping malls and public buildings offer a safe haven during extreme heat. Urban equipment and materials, such as shaded seating areas and water surfaces which reflect light, help cool the environment by offering shade and reflecting heat. Green infrastructure, including parks, urban forests, urban gardens, green squares, etc. reduces temperature through evapotranspiration and shading. Advanced technologies such as cool roofs, intelligent irrigation systems, passive cooling methods and special materials that respond to changes in meteorological conditions can also be used to improve urban cooling performance. By integrating these strategies, cities can effectively face UHIs, creating cooler and more resilient urban spaces for their inhabitants.

CLOSING REMARKS

The UHI phenomenon – general information

Anthropogenic modifications of natural spaces within urbanized areas have led to changes in weather conditions that are monitored within the frames of UHI impact research. Although the negative effects of UHIs have been observed in smaller urban areas, they are even more pronounced in larger urban areas. By monitoring changes in weather patterns, it is possible to identify and link the main factors influencing UHIs and, on that basis, recommend the most effective measures for the mitigation of the negative UHI effects.

UHIs in the context of Croatia

The negative UHI impact on the urban population and visitors is particularly pronounced in major Croatian cities and tourist destinations in the summer months. When it comes to an increase of this impact due to climate change, particular emphasis is placed on the Mediterranean part of the coastal area, where this process is most pronounced. Apart from the climate, the coastal, mountainous and continental parts of Croatia also differs with regard to the relief, city morphology and materials traditionally used in construction, all of which are factors that in a specific way enhance or reduce UHI effects. For this reason, before mitigation measures are defined, it is important to define all regionally-specific factors. A well-thought-out approach to the process of planning and implementation of urban heat load mitigation measures is of explicit importance and must take into account the specificities of the landscape in which the city is located, in particular the geographical, climate and urban specificities.

Climate change factors affecting UHI effects

The climate factors with the greatest negative contribution to UHI effects include an increase in temperature, longer duration of heatwaves and changes in precipitation regimes. They represent an additional negative impact on the heat and heat stress of the urban residents. These are all very good reasons for planning and carrying out activities aimed at reducing the negative UHI effects in cities.

The impact of spatial planning and construction on the effects of UHIs

The scientific community has already proven how important urban planning and design are for the intensity of UHIs. Considering the expected increase in city population, emphasis in spatial planning should be placed on the introduction of good practices and innovative measures focused on the mitigation of negative UHI effects. Spatial planning and the construction method are directly reflected in the manifestation of UHIs, so it is necessary that, in the decision-making phase, these processes take into consideration the results of UHI focused research. Furthermore, spatial planning documentation and construction rules and standards must also include measures that will mitigate and prevent the negative effects of UHIs both in buildings and in the built-up urban environment. In order to take into account all the complexities of UHI-related interrelationships and impacts, spatial planning and construction processes require a multidisciplinary approach and the involvement of a wide range of experts and representatives of the public.

UHI impact on the environment and health

The negative impact of UHIs has been studied through a number of scientific research in the world and Croatia. Of course, the most important negative UHI impacts affect human health, with socially vulnerable groups being at particularly high level of risk from. The appropriate solutions to this issue have yet to be found. Among other impacts, the increased energy consumption (for cooling) and its consequences on pollution, habitat fragmentation and the increased risk of fires that may further deteriorate the quality of life in urban areas should not be overlooked. The conclusions of the studies Croatian researchers have conducted are in line with the conclusions of global research and contribute significantly to the understanding of the importance of UHI mitigation measures.

UHI identification and mapping
There are already a number of methods for UHI research, and they differ with regard to the purpose of research, input data, precision and complexity. The three most commonly used methods are numerical modelling, analysis of remote sensing data and field measurements.

Taking into account all the specificities of Croatian territory, as well as the data sources, availability and structure, here is a proposed methodology that combines the data on land use from the basic topographic database (BTD), the data from the multisensor aerial imaging of Croatia and the process of mathematical modelling of solar radiation.

For developing the methodology further, modelling based on remote measurements of the surface temperature of the soil is suggested, as is referencing this data with the data on land types by cover and purpose.

Implementing measures into space planning and material technology
When creating spatial plans (or their amendments), it is important to adapt land use to the climate context in question, and to define the implementation rules for measures aimed at parts of urban settlements with the greatest exposure to UHI effects determined. When new interventions are planned, it is necessary to take into account the spatial characteristics that contribute to the creation of UHIs (in order to avoid them), as well as the construction measures that can be legally stipulated, and also help reduce the effects of UHIs. This is specifically referring to:

- the morphology and orientation of buildings and their interrelationship (the formation of cool corridors is desirable)
- the typology, proportions and shape of buildings (in terms of thermal protection)
- the selection of materials (it is recommended to use high energy efficiency materials, as well as heat reflective paints and materials)
- the implementation of nature-based solutions (e.g. green roofs and facades)
- an increase in/prescription of the share of green spaces
- encouragement with regard to increasing the diversity of public green spaces and the interconnection of green spaces and green infrastructure systems where special constraints apply;
- a comprehensive approach to UHI issues in areas suitable for comprehensive renovation (prescribing measures for urban rehabilitation and urban transformation).

In terms of mitigating the negative effects of UHIs and strengthening the resilience of cities to extreme weather events, in addition to spatial planning, other instruments and tools available include:

- Green Urban Renewal Strategies (GURS; it is important to include UHI identification and mapping results)
- demographic predictions and analyses
- elaboration of scenarios for predictions with regard to climate change impacts
- tools for modelling (overheating, noise, air quality, etc.)
- models of public engagement for the participatory management of urban spaces (workshops, focus groups, survey questionnaires and research)
- economic instruments (providing co-financing to projects under the Operational Programme Competitiveness and Cohesion 2021– 2027, National Recovery and Resilience Plan, etc.)
- project management tools
- education, continuous professional development and dissemination of awareness (for administrators, decision-makers and the general public).

Green and blue infrastructure
Green and blue infrastructure in interaction with the environment has proven to mitigate the negative effects of UHI. Their effectiveness thereby depends on the size of the space: the larger the affected area, the greater the positive effect on the surrounding space, as has been confirmed by many studies. By employing positive practices in urban planning, it is possible to synergistically increase cooling effects in urban spaces. Additionally, the type of cover and the purpose of the premises, the typology of green infrastructure and the development of specific legal and regulatory frameworks made to enable the long-term preservation and stability of green infrastructure elements play an important role in this process.

Mitigating the effects of UHIs in cities requires a comprehensive approach involving different urban elements, open spaces, urban equipment and materials, green infrastructure and technology. The design and orientation of urban areas play a key role in controlling air flow and exposure to sunlight. Adequate positioning of buildings is especially important when it comes to narrow streets, open spaces can ensure better airflow and shading, whereas large shopping malls and public buildings offer a safe haven during extreme heat. Urban equipment and materials, blue and green infrastructure elements, as well as advanced technologies such as cold roofs, intelligent irrigation systems, passive cooling methods and special tools that respond to changes in meteorological conditions can also help cool the environment. By adopting these solutions, cities can effectively tackle urban heat islands, creating more comfortable and resilient spaces for their residents.

LITERATURE

1. Adams Q. H., Chan E. M. G., Spangler K. R., Weinberger K. R., Lane K. J., Errett N. A., Hess J. J., Sun Y., Wellenius G. A., Nori-Sarma A., 2023. Examining the Optimal Placement of Cooling Centres to Serve Populations at High Risk of Extreme Heat Exposure in 81 US Cities. Public Health Rep. 2023 Nov-Dec 138(6): 955-962. doi: 10.1177/00333549221148174.
2. Herdt A. J., Brown R. D., Scott-Fleming I., Cao G., MacDonald M., Henderson D., Vanos J. K., 2018. Outdoor Thermal Comfort during Anomalous Heat at the 2015 Pan American Games in Toronto, Canada. Atmosphere 9(8): 321. https://doi.org/10.3390/atmos9080321.
3. Ambrosini D., Galli G., Mancini B., Nardi I., Sfarra S., 2014. Evaluating Mitigation Effects of Urban Heat Islands in a Historical Small Center with the ENVI-Met® Climate Model. Sustainability 6(10): 7013–7029. https://doi.org/10.3390/su6107013.
4. Arias P. A., Bellouin N., Coppola E., Jones R. G., Krinner G., Marotzke J., Naik V., Palmer M. D., Plattner G.-K., Rogelj J., 2021. The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Technical Summary In Climate Change 2021: [Masson-Delmotte V., Zhai P., Pirani A., Connors S. L., Péan C., Berger S., Caud N., Chen Y., Goldfarb L., Gomis M. I., Huang M., Leitzell K., Lonnoy E., Matthews J. B. R. Maycock T. K., Waterfield T., Yelekçi O., Yu R. and Zhou B. (eds.)]. Cambridge University Press. In Press
5. Bednar-Friedl B., Biesbroek G. R., Schmidt D. N., Alexander P., Børsheim K. Y., Carnicer J. et al. Europe: from Chapters and Cross-Chapter Papers. In Pörtner H. O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., editors, Climate Change 2022: Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. 2022, p. 1817–1927. doi: 10.1017/9781009325844.01
6. Black-Ingersoll F., de Lange J., Heidari L., Negassa A., Botana P., Fabian M. P., Scammell M. K. A Literature Review of Cooling Center, Misting Station, Cool Pavement, and Cool Roof Intervention Evaluations. Atmosphere. 2022; 13(7): 1103. https://doi.org/10.3390/atmos13071103
7. Boras M., Herceg-Bulić I., Žgela M., Nimac I., 2023. Temperature characteristics and heat load in the City of Dubrovnik. Geofizika Journal, 39(2). 259–279. https://doi.org/10.15233/gfz.2022.39.16
8. Bouyer, J. & Musy, M. (2009). MITIGATING URBAN HEAT ISLAND EFFECT BY URBAN DESIGN: FORMS AND MATERIALS.
9. Bozonnet E., Musy M., Calmet I., Rodriguez F., 2015. Modeling methods to assess urban fluxes and heat island mitigation measures from street to city scale, International Journal of Low-Carbon Technologies, 10(1): 62–77, https://doi.org/10.1093/ijlct/ctt049.
10. Brocherie F., Girard O., Millet G. P. Emerging Environmental and Weather Challenges in Outdoor Sports. Climate. 2015; 3(3):492–521. https://doi.org/10.3390/cli3030492
11. Brown, Helen & Proust, Katrina & Newell, Barry & Spickett, Jeffery & Capon, Tony & Bartholomew, Lisa. (2018). Cool Communities—Urban Density, Trees, and Health. International Journal of Environmental Research and Public Health. 15. 1547. 10.3390/ijerph15071547.
12. Cedilnik R., 2015. Determination of land surface temperature from Landsat satellite imagery: Master’s Thesis (“Določanje temperature tal iz satelitskih posnetkov Landsat: Magistrsko delo”), University of Ljubljana, Faculty of Civil and Geodetic Engineering. https://repozitorij.uni-lj.si/IzpisGradiva.php?id=32772.
13. Chakraborty T., Ferreira C. M., Corcoran, 2019. Urban Heat Island Effect and Its Impact on Residential Housing in St. Louis. Urban Science 3(1): 11.
14. Cheela V. R. S., John M., Biswas W., Sarker P. , 2021. Combating Urban Heat Island Effect – A Review of Reflective Pavements and Tree Shading Strategies. Buildings. 2021; 11(3):93. https://doi.org/10.3390/buildings11030093.
15. Chmielewski F. M., Rötzer T. (2001). Response of tree phenology to climate change across Europe. Agricultural and Forest Meteorology, 108(2), 101–112.

16. Chow W. T. L., Salamanca F., Georgescu M., Mahalov A., Jeffrey M. Milne, Ruddell B. L., 2014. A multi-method and multi-scale approach for estimating city-wide anthropogenic heat fluxes. Atmospheric Environ., 99: 64–76. https://doi.org/10.1016/j.atmosenv.2014.09.053
17. Copernicus Land Monitoring Service. (b. d.-a). Mapping guide – Urban Atlas Land Cover/Land Use and Street Tree Layer 2012 and 2018. Obtained on February 20, 2024, ftom https://land.copernicus.eu/en/products/urban-atlas/urban-atlas-2018.
18. Copernicus Land Monitoring Service. (b. d.-b). Urban Atlas Land Cover/Land Use 2018 (vector), Europe, 6-yearly [dataset]. https://doi.org/10.2909/fb4dffa1-6ceb-4cc0-8372-1ed354c285e6.
19. Cvitan L., Sokol Jurković R., 2016. Secular trends in monthly heating and cooling demands in Croatia. Theoretical and Applied Climatology 125: 565–581. https://doi.org/10.1007/s00704-015-1534-7
20. De Ridder K., Lauwaet D., Maihe B., Vankerkom J., 2016. Assessment of the energy demand reduction potential of cool roofs in Europe. Energy and Buildings, 119: 270-279.
21. Ding F., Pang H., Guo W., 2018. Impact of the urban heat island on residents' energy consumption: a case study of Qingdao, doi: 10.1088/1755-1315/121/3/032026.
22. Djedjig R., Bozonnet E., Belarbi R., 2015. Experimental study of the urban microclimate mitigation potential of green roofs and green walls in street canyons. International Journal of Low-Carbon Technologies, Volume 10(1): 34–44, https://doi.org/10.1093/ijlct/ctt019.
23. Dodman D., Hayward B., Pelling M., Castan Broto V., Chow W., Chu E., Dawson R., Khirfan L., McPhearson T., Prakash A., Zheng Y., Ziervogel G., 2022. Cities, Settlements and Key Infrastructure. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M. Langsdorf S., Löschke S., Möller V., Okem A., Rama B. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 907–1040, doi:10.1017/9781009325844.008.
24. European Environment Agency. (b. d.). CORINE Land Cover 2018 (vector/raster 100 m), Europe, 6-yearly [dataset]. Downloaded: March 11, 2024. https://land.copernicus.eu/en/products/corine-land-cover/clc2018
25. European Environment Agency. (b. d.). Urban Atlas Building Height 2012 (raster 10 m), Europe—Version 3, Oct. 2022. EEA geospatial data catalogue. Obtained: March 12, 2024, https://sdi.eea.europa.eu/catalogue/copernicus/api/records/42690e05-edf4-43fc-8020-33e130f62023
26. Fowler T., Sadohara S., Yoshida S., 2009. Designing landuse patterns to mitigate the urban heat island phenomenon in consideration of ocean wind flow and openspace voids. Journal of Architecture and Planning (transactions of Aij) 74:2223-2229. doi:10.3130/aija.74.222 .
27. Gangwisch M., Saha S., Matzarakis A., 2023. Spatial neighborhood analysis linking urban morphology and green infrastructure to atmospheric conditions in Karlsruhe, Germany. Urban Climate, 51, 101624.
28. Grundstein A., Williams C., 2018. Heat Exposure and the General Public: Heath Impacts, Risk Communication, and Mitigation Measures 10.1007/978-3-319-75889-3_3, pp. 29–43.
29. Guo A., Yang J., Xiao X., Xia J., Jin C., Li X., 2020. Influences of urban spatial form on urban heat island effects at the community level in China. Sustainable Cities and Society, 53, 101972.
30. Holz I., Franzaring J., Böcker R., Fangmeier A., 2011. Entry dates of phenological phases and their relationship to weather and climate ("Eintrittsdaten phänologischer Phasen und ihre Beziehung zu Witterung und Klima"); LUBW: Karlsruhe, Germany.
31. Hong B., Lin B., 2015. Numerical studies of the outdoor wind environment and thermal comfort at pedestrian level in housing blocks with different building layout patterns and trees arrangement, Renewable Energy 73: 18–27, https://doi.org/10.1016/j.renene.2014.05.060.
32. Holz I., Franzaring J., Böcker R., Fangmeier A., 2011. Entry dates of phenological phases and their relationship to weather and climate ("Eintrittsdaten phänologischer Phasen und ihre Beziehung zu Witterung und Klima"); LUBW: Karlsruhe, Germany.
33. Hooyberghs H., Lauwaet D., Lefebvre W., Driesen G., Van Looy S., Wouters H., ... and Hamdi R., 2017. Modelling the impact of urban heat islands on energy demand and electricity use in the Greater Paris region. Energy and Buildings 155: 63–78.

34. Huang Q., Huang J., Yang X., Fang C., Liang Y., 2019. Quantifying the seasonal contribution of coupling urban land use types on Urban Heat Island using Land Contribution Index: a case study in Wuhan, China. Sustain Cities Soc 44: 666–675.
35. Humaida N., Saputra H., Sutomo, Hadiyan Y, 2023. Urban gardening for mitigating heat island effect. IOP Conference Series: Earth and Environmental Science, Volume 1133, International Conference on Modern and Sustainable Agriculture 2022 02/08/2022 – 03/08/2022 Online, DOI 10.1088/1755-1315/1133/1/012048
36. Ivajnšič D., Donša D., Grujić V. J., Pipenbaher N. (2022). Case Studies of Climate Change Effects Spatial Analysis: A monograph Based on Findings from the Project Preventing Heat Stress in Urban Systems Under Climate Change (ARRS J7-1822) ("Primeri prostorskih analiz vplivov podnebnih sprememb: Monografija v okviru projekta Preprečevanje toplotnega stresa v urbanih sistemih v luči podnebnih sprememb (ARRS J7-1822)"). In: University of Maribor Press. University of Maribor Press. https://doi.org/10.18690/um.fnm.8.2022.
37. Kandya A., Mohan M., 2018. Mitigating the Urban Heat Island effect through building envelope modifications, Energy and Buildings, Volume 164:266-277. https://doi.org/10.1016/j.enbuild.2018.01.014.
38. Lauwaet D., Hooyberghs H., Maiheu B., Lefebvre W., Driesen G., Van Looy S. 2016. How relevant are urban heat island intensity measures considering the energy demand of different income groups? Renewable and Sustainable Energy Reviews 60: 739–748.
39. Leal Filho W., Wolf F., Castro-Díaz R., Li C., Ojeh V. N., Gutiérre N., Nagy G. J., Savić S., Natenzon C. E., Al-Amin A. Q., Maruna M., Böneck J., 2021. Addressing the urban heat islands effect: A cross-country assessment of the role of green infrastructure. Sustainability 13(2): 753. https://doi.org/10.3390/su13020753.
40. Li D., Bou-Zeid E., 2013. Synergistic interactions between urban heat islands and heat waves: The impact in cities is larger than the sum of its parts. Journal of Applied Meteorology and Climatology 52(9): 2051–2064.
41. Liu B., Guo X., Jiang J., 2023. How Urban Morphology Relates to the Urban Heat Island Effect: A Multi-Indicator Study. Sustainability.; 15(14):10787. https://doi.org/10.3390/su151410787.
42. Loh N., Bhiwapurkar P., 2021. Urban heat-mitigating building form and façade framework. Architectural Science Review 65(10): 1–15. https://doi.org/10.1080/00038628.2021.1924610.
43. Manoli G., Fatichi S., Bou-Zeid E., Sun T., Masselot P., Huang W. T. K., 2023. Assessing the impact of urban heat islands on the risks and costs of temperature-related mortality, EGU General Assembly 2023, Vienna, Austria, 23–28 Apr 2023, EGU23-9892. https://doi.org/10.5194/egusphere-egu23-9892.
44. Fog S., Lodi C., Lombroso L., Muscio A., Teggi S., 2015. Analysis of the urban heat island effects on building energy consumption. International journal of energy and environmental engineering 6(1): 91-99. doi: 10.1007/s40095-014-0154-9.
45. Merhej R., 2019. Stigma on mental illness in the Arab world: beyond the socio-cultural barriers. International Journal of Human Rights in Healthcare 12(4): 285–298. https://doi.org/10.1108/IJHRH-03-2019-0025
46. Mesarić M., Rupčić M., Gudac I., Leljak M., Radaković M., Stojak J., 2019. Climate Change Adaptation Plan for the City of Dubrovnik ("Plan prilagodbe klimatskim promjenama grada Dubrovnika"), IRES Ekologija, pp. 1–63.
47. Mitchell B., Chakraborty J., 2018. Thermal Inequity: The Relationship between Urban Structure and Social Disparities in an Era of Climate Change. In: The Routledge Handbook of Climate Justice [Jafry T. (ed.)]. Routledge, Oxon, 330–346.
48. Mohan M., Kikegawa Y., Gurjar B. R., Bhati S., Kolli N. R., 2013. Assessment of urban heat island effect for different land use–land cover from micrometeorological measurements and remote sensing data for megacity Delhi. Theor Appl Climatol 112, 647–658. https://doi.org/10.1007/s00704-012-0758-z
49. Moosavi F. H., Mahdavi M. (2017). Reducing Heat and Urban Competition With Water.
50. Mora C., Dousset B., Caldwell I. R., Powell F. E., Geronimo R. C., Bielecki C. R., Counsell C. W. W., Dietrich B. S., Johnston E. T., Louis L. V., Lucas M. P., McKenzie M. M., Shea A. G., Tseng H., Giambelluca

T. W., Leon L. R., Hawkins E. E. ORCID: https://orcid.org/0000-0001-9477-3677, Trauernicht C, 2017. Global risk of deadly heat. Nat. Clim. Change, 7 (7): 501–506. https://doi.org/10.1038/nclimate3322

51. Morini E., Castellani B., De Ciantis S., Anderini E., Rossi F., 2018. Planning for cooler urban canyons: Comparative analysis of the influence of façades reflective properties on urban canyon thermal behavior, Solar Energy 162: 14–27. https://doi.org/10.1016/j.solener.2017.12.064.
52. Mossel C., Ameling L., Zaradich M., Woody M. A., Foley E., Mbaye S., Blake R. A., Norouzi H., 2023. Quantifying the Cooling Impact of Urban Heat Island Mitigation Strategies at the Neighborhood Scale. IGARSS 2023: 2092–2094. doi: 10.1109/IGARSS52108.2023.10282652
53. MPGI – Ministry of Physical Planning, Construction and State Property (2021). The Urban Green Infrastructure Development Programme for 2021-2030 ("Program razvoja zelene infrastrukture u urbanim područjima za razdoblje od 2021. do 2030. godine"). Zagreb, 2021. https://mpgi.gov.hr/UserDocsImages/dokumenti/EnergetskaUcinkovitost/Program_razvoja_zelene_infrastrukture_do_2030.pdf
54. Oberoi A., Mullan K., 2019. Urban Heat Island and Residential Property Values: A Systematic Review. Sustainability, 11(6): 1633.
55. Oke T. R., Mills G., Christen A., Voogt J. A., 2017: Urban Climates. Cambridge University Press, Cambridge. https://doi.org/10.1017/9781139016476.
56. Onishi A., Cao X., Ito T., Shi F., Imura H., 2010. Evaluating the potential for urban heat-island mitigation by greening parking lots. Urban Forestry & Urban Greening, 9(4):323-332. https://doi.org/10.1016/j.ufug.2010.06.002.
57. Peluso P., Persichetti G., Moretti L., 2022. Effectiveness of Road Cool Pavements, Greenery, and Canopies to Reduce the Urban Heat Island Effects. Sustainability 14(23): 16027. https://doi.org/10.3390/su142316027.
58. Pramanik S., Punia M., 2020. Land use/land cover change and surface urban heat island intensity: source–sink landscape-based study in Delhi, India. Environment, Development and Sustainability 22: 7331–7356. DOI:10.1007/s10668-019-00515-0.
59. Pratiwi S. N., 2018. A review of material cover features for mitigating urban heat islands. International Journal on Livable Space, 3(2), 71–80. https://doi.org/10.25105/livas.v3i2.3196.
60. Priyadarsini R., Wong N., Cheong K. W. D., 2008. Microclimatic modeling of the urban thermal environment of Singapore to mitigate urban heat island. Solar Energy, 82(8): 727–745, https://doi.org/10.1016/j.solener.2008.02.008.
61. Quintana-Talvac C., Corvacho-Ganahin O., Smith P., Sarricolea P., Prieto M., Meseguer-Ruiz O., 2021. Urban Heat Islands and Vulnerable Populations in a Mid-Size Coastal City in an Arid Environment. Atmosphere, 12(7): 917. https://doi.org/10.3390/atmos12070917.
62. Radhi H., Assem E., Sharples S., 2014. On the colours and properties of building surface materials to mitigate urban heat islands in highly productive solar regions, Building and Environment 72: 162–172. https://doi.org/10.1016/j.buildenv.2013.11.005.
63. Rendana M., Idris W. M. R., Rahim S. A., et al. 2023. Relationships between land use types and urban heat island intensity in Hulu Langat district, Selangor, Malaysia. Ecol Process 12, 33. https://doi.org/10.1186/s13717-023-00446-9
64. Roloff A., 2013. Trees in a city ("Bäume in der Stadt"). 110, Ulmer Verlag: Stuttgart, Germany.
65. Rosso F., Castellani B., Presciutti A., Morini E., Filipponi M., Nicolini A., Santamouris M., 2015. Retroreflective façades for urban heat island mitigation: Experimental investigation and energy evaluations. Applied Energy 145: 8–20. https://doi.org/10.1016/j.apenergy.2015.01.129.
66. Rosso F., Golasi I., Castaldo V. L., Piselli C., Pisello A. L., Salad F., Ferrero M., Cotana F., de Lieto Vollaro A., 2018. On the impact of innovative materials on outdoor thermal comfort of pedestrians in historical urban Canyons, Renewable Energy, Volume 118: 825–839. https://doi.org/10.1016/j.renene.2017.11.074
67. Ruiz-Aviles V., Brazel A., Davis J. M., Pijawka D., 2020. Mitigation of Urban Heat Island Effects through "Green Infrastructure": Integrated Design of Constructed Wetlands and Neighborhood Development. Urban Sci. 4(4): 78. https://doi.org/10.3390/urbansci4040078.

68. Sabrin S, Karimi M, Nazari R, 2020. Developing Vulnerability Index to quantify Urban Heat Islands Effects Coupled with Air Pollution: A Case Study of Camden, NJ, ISPRS Int. J. of Geo-Inf. 9(6):349. https://doi.org/10.3390/ijgi9060349.
69. Santamouris M, 2020. Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change. Energy Build. 207, 109482. https://doi.org/10.1016/j.enbuild.2019.109482.
70. Schwarz N, Manceur AM, 2015. Analyzing the Influence of Urban Forms on Surface Urban Heat Islands in Europe. Journal of Urban Planning and Development-ASCE, 141(3). https://doi.org/10.1061/(ASCE)UP.1943-5444.0000263.
71. Sen S., Fernandèz J. P. R. M.–R., Roesler J., 2020. Reflective Parking Lots for Microscale Urban Heat Island Mitigation. Transportation Research Record, 2674(8), 663-671. https://doi.org/10.1177/0361198120919401.
72. Seletković A., Kičić M., Ančić M., Kolić J., Pernar. R, 2023. The Urban Heat Island Analysis for the City of Zagreb in the Period 2013-2022 Utilising Landsat 8 Satellite Imagery. Sustainability. 15. 3963. 10.3390/su15053963
73. Shi L., Imhof M. L., Zhang P., 2020. Spatial and Temporal Variations in the Cooling Effect of Urban Parks on the Urban Heat Island Effect in Phoenix, Arizona, USA. Remote Sensing, 12(1), 34.
74. Stanley C. H., Helletsgruber C., Hof A., 2019. Mutual influences of urban microclimate and urban trees: an investigation of phenology and cooling capacity, Forests (MDPI AG) Vol. 10(7): 533.
75. Smid M., Russo S., Costa A. C., Granell C., Pebesma E., 2019. Ranking European capitals by exposure to heat waves and cold waves. Urban Clim. 27:388–402. https://doi.org/10.1016/j.uclim.2018.12.010Get rights and content.
76. Steeneveld G. J., Koopmans S., Heusinkveld B. G., Theeuwes N. O., 2014. Refreshing the role of open water surfaces on mitigating the maximum urban heat island effect, Landscape and Urban Planning 121: 92–96. https://doi.org/10.1016/j.landurbplan.2013.09.001.
77. Stewart I. D., Oke T. R., 2012. Local climate zones for urban temperature studies. Bulletin of the American Meteorological Society, 93, 1879–1900. https://doi.org/10.1175/BAMS-D-11-00019.1
78. Susca, T. Pomponi F., 2020. Heat Island Effects in Urban Life Cycle Assessment: Novel insights to include the effects of the urban heat island and UHI-mitigation measures in LCA for effective policy making. J. Ind. Ecol. 24(2): 410–423. https://doi.org/10.1111/jiec.12980.
79. Szkordilisz F., 2014. Mitigation of urban heat island by green spaces. Pollack Periodica. 9(1): 91–100. https://doi.org/10.1556/pollack.9.2014.1.10.
80. Taleghani M., Swan W., Johansson E., Ji Y., 2021. Urban cooling: What façade orientation has the most impact on a microclimate? Sustainable Cities and Society, Volume 64,102547. https://doi.org/10.1016/j.scs.2020.102547.
81. Teruaki I., 2006. Structure and Function in Urban Landscape in term of reduction of Heat Island by green space.
82. Tomasović S., Sremec J., Košćak Lukač J., Sičaja G., Bačić Baronica K., Ostojić V., Raifi, Tomić Sremec N., Plačko-Vršnak D., Srnec L., Mikec K., 2022. Weather patterns and occurrence of epileptic seizures. BMC Neurology 22(1): 33. https://doi.org/10.1186/s12883-021-02535-8
83. Tzavali A, Founda D, Santamouris M (2015). The Role of Urban Heat Island in Urban Heat Waves with a Case Study for Athens, Greece. Sustainable Cities and Society, 14, 42-51.
84. Ueyama M., Ando T., 2020. Cooling effect of an urban park by enhanced heat transport efficiency. Journal of Agricultural Meteorology 76(3):148–153. https://doi.org/10.2480/agrmet.D-20-00022
85. Unger J., Sümeghy Z., Zoboki J., 2001 Temperature cross-section features in an urban area. Atmospheric research, 58(2), 117-127. 10.1016/S0169-8095(01)00087-4.
86. U.S. Environmental Protection Agency. 2008. “Urban Heat Island Basics.” In: Reducing Urban Heat Islands: Compendium of Strategies. Draft. https://www.epa.gov/heat-islands/heat-island-compendium
87. World Bank, 2020. Analysis of Heat Waves and Urban Heat Island Effects in Central European Cities and Implications for Urban Planning. Washington, D.C.: World Bank.

88. Wouters H. et al., 2017. Heat stress increase under climate change twice as large in cities as in rural areas: A study for a densely populated midlatitude maritime region. Geophys. Res. Lett, 44(17): 8997–9007. https://doi.org/10.1002/2017GL074889op.
89. Xu L, Wang J, Xiao F, EI-Badawy S, Awed A, 2021. Potential strategies to mitigate the heat island impacts of highway pavement on megacities with considerations of energy uses. Applied Energy 281, 116077, https://doi.org/10.1016/j.apenergy.2020.116077
90. Yuan C., Mei S., He W., Adelia A. S., Zhang L., 2021. Mitigating Intensity of Urban Heat Island by Better Understanding on Urban Morphology and Anthropogenic Heat Dispersion, EMS Annual Meeting 2021, online, 6–10 Sep 2021, EMS 2021-1, https://doi.org/10.5194/ems2021-1.
91. Zaninović K., Matzarakis A., 2014. Impact of heat waves on mortality in Croatia. International Journal of Biometeorology 58: 1135–1145. https://doi.org/10.1007/s00484-013-0706-3.
92. Zaninović K., 2003. The influence of meteorological parameters on the acute neurovegetative disability, ECAM 2003, Rome, 15 -19. 9.
93. Zaninović K., Gajić-Čapka M., 2008. Climate change and the influence on health ("Klimatske promjene i utjecaj na zdravlje"), Croatian Journal of Infection 28(1): 5–15.
94. Zaninović K., Gajić-Čapka M., Perčec Tadić M., Vučetić M., Milković J., Bajić A., Cindrić K., Cvitan L., Katušin Z., Kaučić D., Likso T., Lončar E., Lonča Ž., Mihajlović D., Pandžić K., Patarčić M., Srnec L., Vučetić V., 2008. Climate Atlas of Croatia/Climate Atlas of Croatia 1961–1990, 1971–2000. Croatian Meteorological and Hydrological Service, Zagreb, p. 200.
95. Zellweger F., De Frenne P., Lenoir J., Vangansbeke P., Verheyen K., Bernhardt-Römermann M. et al., 2020. Forest microclimate dynamics drive plant responses to warming. Science 368(6492): 772-775. https://doi.org/10.1126/science.aba6880.
96. Zhao L., Oleson K., Bou-Zeid E. et al., 2021: Global multi-model projections of local urban climates. Nat. Clim. Chang. 11(2): 152–157. https://doi.org/10.1038/s41558-020-00958-8.
97. Zipper S. C., Schatz J., Singh A., Kucharik C. J., Townsend P. A. Loheide II, S.P. Urban heat island impacts on plant phenology: Intra-urban variability and response to land cover. Environ. Res. Lett. 2016, 11, 1–12.
98. Zou Z, Yan C, Yu L, Jiang X, Ding J, Qin L, Wang B, Qiu G, 2021. Impacts of land use/land cover types on interactions between urban heat island effects and heat waves. Building and environment, 204:108138. DOI:10.1016/j.buildenv.2021.108138.
99. Žgela M, 2018. Urbana klimatologija – Primjer toplinskog otoka grada Zagreba. Geografski horizont, 64(2), 33–42. https://hrcak.srce.hr/220514.
100. Žgela M, Herceg-Bulić I, Lozuk, J, Jureša P, 2024. Linking land surface temperature and local climate zones in nine Croatian cities. Urban Climate, 54. https://doi.org/10.1016/j.uclim.2024.101842.
101. Žiberna I. 2022. Seasonal regime of surface urban heat islands in Maribor ("Sezonski režim površinskega mestnega toplotnega otoka v Mariboru"). In: D. Ivajnšič, Examples of spatial analyses of climate change impacts: A monograph Based on Findings from the Project Preventing Heat Stress in Urban Systems Under Climate Change (ARRS J7-1822) ("Primeri prostorskih analiz vplivov podnebnih sprememb: Monografija v okviru projekta Preprečevanje toplotnega stresa v urbanih sistemih v luči podnebnih sprememb (ARRS J7-1822)"). University of Maribor Press. https://doi.org/10.18690/um.fnm.8.2022.