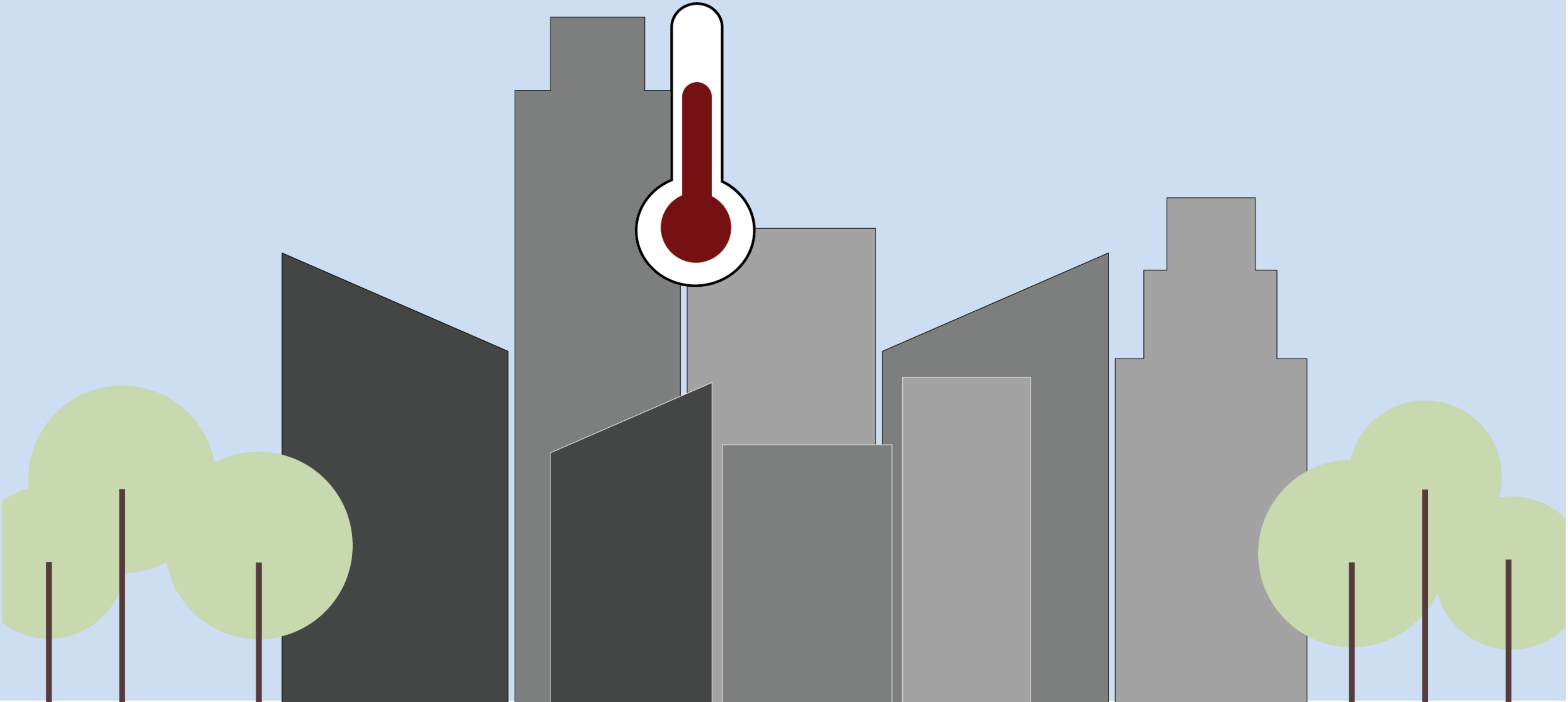
HANDBOOK ON MITIGATING URBAN HEAT ISLANDS



IMPRESUM

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EFFECT OF URBAN HEAT ISLANDS AND DEVELOPMENT FACTORS

With the development of cities, changes in space and landscape inevitably occur, as buildings, roads and other built infrastructure replace natural areas. In natural areas, surfaces are permeable and moist. During urbanization, however, they are transformed into dry and impermeable surfaces, and the construction affects the direction and speed of the wind. **Such changes in land use lead to the formation of urban heat islands (UHI).**

UHI is a climatic phenomenon that causes higher surface and air temperatures in urban areas compared to rural and natural environments. It is precisely this temperature difference that constitutes the UHI. The annual average air temperature of a large city with a population of one million or more can be 1 to 3°C higher than the ambient air temperature. During calm nights, the temperature difference can reach up to 10°C. Even smaller towns and settlements face heat islands, but they are less pronounced. The intensity of UHI occurrence is related to the volume of built-up areas, building density, human activities, socioeconomic impacts, proportion of vegetation (especially dendrological species), weather conditions, etc.

This Handbook has been developed to enable the Ministry of Physical Planning, Construction and State Assets to provide local self-government units (LGUs) with a framework for identifying UHIs and to provide a set of framework guidelines with a special focus on green urban renewal measures. One aspect of this Handbook is the methodology for identifying the effects of UHIs, which takes into account various characteristics such as built-up and surface use, as well as a review of possible mitigation guidelines. The Handbook contains illustrative examples of good practice to facilitate the transfer of knowledge to local authorities and relevant stakeholders.

FACTORS THAT AFFECT THE FORMATION OF THE URBAN HEAT ISLAND EFFECT

Climatic factors play a key role in the formation and intensification of UHIs. Air temperature, relative humidity, wind and precipitation have a major impact on this phenomenon. High temperatures caused by anthropogenic activities such as **transport and industry contribute to the increase of surface and air temperatures in urban areas**. Reduced air humidity further intensifies the effect of heat islands as urbanized areas are less humid and more prone to heating. Reduced wind speed in urban areas hinders heat dispersion, and changes in humidity can affect thermal comfort and increase heat stress for residents. During heatwaves, the effect of heat islands is amplified, but the level varies depending on the location and time.

In the future, the risks of heatwaves for cities and infrastructure will worsen even more. Depending on the greenhouse gas emissions scenario, a large portion of the population could be exposed to extreme heat and humidity by the end of the century, with cities in mid-latitude regions being particularly vulnerable to these risks. Climate change is already having a major impact on the urban environment, and higher temperatures and altered weather patterns will only exacerbate the situation. **The impact of climate change on UHIs is complex, involving interactions between meteorological, environmental and spatial factors**.

OVERVIEW OF CLIMATIC FACTORS

INCREASED AIR TEMPERATURE DUE TO CLIMATE CHANGE

Average temperatures in urban areas of Europe have increased by 1 to 3 °C, causing increased heat load. High temperatures affect the heating of urban areas such as asphalt roads, buildings and roofs, which leads to an increase in temperature within cities.

MORE FREQUENT AND INTENSE HEATWAVES

The number of days with extremely high temperatures (above 35°C) has increased in Europe, causing more frequent and intense heatwaves. Climate change leads to earlier onset and longer duration of heatwaves, further increasing temperature differences between the city and its surrounding.

CHANGES IN PRECIPITATION PATTERNS

Climate change brings changes in precipitation patterns, which can affect the water balance in urban areas. Drought periods during summer further intensify the effects of UHIs, while lack of water can limit cooling options and water supply.

PROJECTIONS OF CLIMATE CHANGE IMPACTS ON HEAT ISLANDS IN CROATIA

Analyses by the Croatian Meteorological and Hydrological Service show an increase in the number of hot days and hot nights in Croatia, especially in Zagreb. The urban heat effect is pronounced, especially due to built concrete surfaces, resulting in a strong heat increase.

OVERVIEW OF OTHER FACTORS

Removal of vegetation in urban areas leads to a reduction of shaded areas and the absence of evapotranspiration processes through which vegetation lowers air temperature.

Properties of building materials such as the reduced ability to reflect sunlight, heat emission and heat capacity affect the temperature increase in cities. As a result, urban centres can absorb and store twice as much heat during the day as their rural surroundings.

Urban morphology affects airflow and the ability of surfaces to emit longwave radiation back into the atmosphere. Due to dense urban construction, surfaces and buildings are often at least partially shielded by neighbouring structures, preventing them from releasing heat quickly and unobstructed.

Anthropogenic heat sources refer to heat produced by human activities in an urban environment, and this heat is estimated as the sum of energy consumed for heating and cooling, appliance operation, transport and industrial processes.

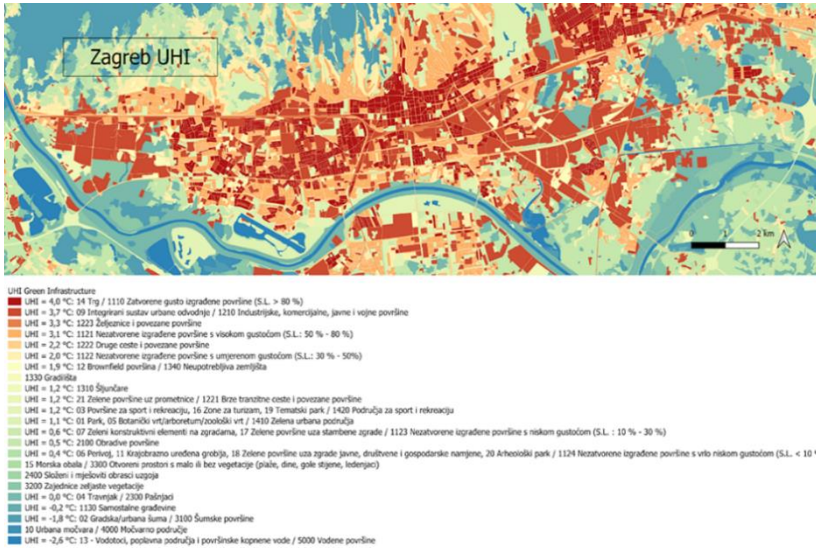
Changes in water balance in cities result from altered surface properties in the city (e.g. large areas covered with impermeable materials). Rapid runoff of rainwater through grey infrastructure and insufficient vegetation in cities reduce transpiration and evaporation of water from the soil, which is reflected in lower absolute and relative air humidity.

Weather and geographical factors such as wind direction and speed, location and local topography of cities influence the creation of the UHIs effect. For example, large water surfaces near cities mitigate temperature fluctuations and reduce temperatures, while cities located in valleys are generally poorly ventilated.

URBAN HEAT ISLANDS IN CROATIA

Analyses by the Croatian Meteorological and Hydrological Service indicate the problem of UHIs caused by climate change. The warming in Croatia is manifested in all temperature extremes indices, such as a significant increase in the number of hot days, an increase in the number of hot days in spring, an increase in the number of hot summer nights on the Adriatic and an extension of warm periods. Significant warming in the interior of Croatia is especially visible in the area of Zagreb, which indicates a strong urban warming effect, and there is a particularly pronounced increase in the number of hot nights due to the increased heating of built concrete surfaces. On an annual basis, there will be at least 12 more hot days throughout the Republic of Croatia in the period from 2041 to 2070 compared to the period from 1981 to 2010. The far east of the country is expected to see an increase of 12 to 15 days, while central Croatia will see an increase of 15 to 18 hot days. The mountainous regions, as well as the inland areas of Dalmatia and Istria, will experience up to 21 more hot days, and the narrow coastal area will have up to 24 more hot days in the period from 2041 to 2070 compared to 1981 to 2010. Annual changes in the duration of warm periods, in accordance with the changes in the number of hot days, gradually increase from the east of the country through the central and mountainous regions and reach the maximum along the coast. This spatial increase, from the east through central and mountainous areas towards the coast, is characteristic of all four seasons, most pronounced in summer and least in winter.

The largest urban area in the Republic of Croatia is Zagreb, with a metropolitan population of about one million, followed by Split and Rijeka, the only Croatian cities with over one hundred thousand inhabitants. While UHIs are often associated with large metropolitan cities, they can also form in smaller cities because they primarily depend on the concentration of artificial materials such as concrete, asphalt, glass, etc. Therefore, it should be emphasized that UHIs will also form in smaller urban areas, which are numerous in Croatia, negatively impacting the health of that part of the population. However, larger cities will experience both a greater negative impact of UHIs and their intensity, i.e. the difference between the temperature of the city centre and its surroundings, compared to smaller towns. The figure below shows the spatial distribution of UHIs in the city of Zagreb, which clearly demonstrates that densely built areas are exposed to higher temperatures compared to the unbuilt, especially green and water areas.



The effect of UHIs on the example of Zagreb according to different types of urban land cover

Urban morphology varies significantly between cities in the territory of the Republic of Croatia and is heavily influenced by physical and geographical characteristics. For example, coastal cities are often more densely populated than continental ones, partly due to natural factors and partly due to economic and commercial reasons that drive littoralization, causing coastal cities to expand within a narrow coastal strip. Many coastal cities are limited by mountainous barriers, preventing expansion inland, while, at the same time, littoralization keeps the majority of the population in the coastal area. As a result, coastal cities have a much more heterogeneous urban morphology than continental cities, which exhibit a much lower complexity of topography and are often located in river plains. Their urban structure is therefore more regular because the expansion of the city could be carried out with a certain level of planning. Additionally, cities with a river flowing through experience a cooling effect due to the presence of a water surface that reduces the heat load. The negative impact of UHIs on the population and visitors of cities is particularly pronounced in larger Croatian cities and tourist destinations in the summer season. As part of the intensification of negative effects due to the impact of the climate, the Mediterranean part of the coastal area stands out, where the effects will be significantly more pronounced than in the mountainous or Pannonian parts of the country. In addition to climate differentiation, among these areas there are differences in features such as the relief environment, urban morphology and traditional materials used in construction, all of which have a specific effect on the intensification or reduction of the negative UHI effects. It is therefore essential to identify all positive and negative factors and to adapt measures to mitigate the negative effects of UHIs.

THE IMPORTANCE OF IDENTIFYING AND MITIGATING URBAN HEAT ISLANDS

The impact of UHIs on the environment and residents' health poses a significant challenge in urban areas around the world. Solar radiation, or thermal energy that reaches urban areas, is the main natural driver of UHI formation, while anthropogenic activities contribute to an increase of this effect. Increased urbanization results in the creation of UHIs, so temperatures are significantly higher than in the surrounding rural areas. The intensity and severity of this phenomenon increase with rising temperatures of an area and the expansion of cities and construction into the surrounding rural and natural areas. This leads to harmful consequences, including changes in ecosystems, increased energy consumption for cooling, and health problems for urban residents.

ENERGY CONSUMPTION

Global warming and UHI effects have **a significant impact on energy consumption in buildings**, particularly increasing the need for air conditioners for cooling. In summer, total electricity consumption and peak energy load can rise by as much as one fifth. For each degree of increase in air temperature in the range from 20 to 25°C, the demand for electricity for air conditioning or cooling in rural areas increases by 3 to 4%. In urban areas, due to additional heating caused by the effects of UHI, the demand for electricity for cooling can increase by an additional 5 to 10%. The highest demand typically occurs during hot summer afternoons on weekdays, when air conditioners, lights and electronic devices are in use. During extreme heat events, which exacerbate the UHI effect, increased use of air conditioners can strain systems or even lead to power outages.

One of the few positive effects of UHIs is the reduction in the energy required for heating residential areas during the cold part of the year. Reducing the need for heating, especially with fossil fuels, has a positive impact on improving air quality and reducing pollution in urban areas. The impact of climate change and UHIs is present in Croatia, too, indicating a correlation between energy consumption and climate change during the warmer and colder parts of the year.

INCREASED GREENHOUSE GAS EMISSIONS AND AIR POLLUTION

A higher demand for electricity for cooling purposes **contributes to higher greenhouse gas emissions and air pollution**, especially due to the extensive use of fossil fuels in the energy sector. These pollutants have a detrimental effect on human health by deteriorating air quality through the formation of ground-level ozone (smog), fine particles and acid rain. Ground-level ozone is formed as a result of the reaction between nitrogen oxides and volatile organic compounds under the influence of sunlight and high temperatures.

THREAT TO HEALTH, PRODUCTIVITY AND REDUCED QUALITY OF LIFE

Heat stress is associated with a range of health issues for urban residents, with the consequences of higher urban temperatures being unevenly distributed among urban populations. Heat islands contribute to higher daytime temperatures, reduced night time cooling and higher levels of air pollution. This leads to heat-related conditions and illnesses, such as general discomfort, respiratory problems, heat cramps, heat exhaustion and heat stroke, which can even be fatal in some cases. The elderly population is among the most vulnerable to extreme heat due to physiological, psychological and socioeconomic factors. Older people, especially women, often have poorer health, are more sensitive to high temperatures, less mobile and isolated, and have low incomes. Children are also more sensitive to extreme heat due to their low body weight, physiological characteristics and lifestyle. For example, children's faster breathing relative to body size, longer time spent outdoors and a developing respiratory system increase the risk of worsening asthma and other lung diseases caused by low-ozone and smog pollution during heat waves. Lower-income populations face greater health risks from heat due to poor housing conditions, such as lack of air conditioning and living in homes with inadequate thermal insulation. During heat waves, individuals with diabetes, physical impairments and cognitive disabilities are particularly at risk. Stabilization of climate warming can significantly reduce health risks for the population during heat waves. Dehydration and heat stress **negatively impact behaviour, learning and cognitive functions across all age groups.** There is also a link between extreme temperatures and an increased incidence of various health issues, such as epileptic seizures and neurological disorders.

Higher temperatures in urban areas create unequal economic burdens for residents and households. In some regions, there is a greater need for the use of air conditioners, leading to high energy consumption during warm periods. Economic burdens are also caused by medical costs related to treating heat-induced illnesses and work absences. Furthermore, disproportionate increases in risks have been recorded for people of lower socioeconomic status exposed to urban heat. These risks arise from inadequate housing conditions, less frequent use and access to air conditioners, and performing physical work outdoors, which exacerbates exposure to heat.

The intensity of UHIs increases with more intense urbanization, negatively affecting property values, occupancy rates and overall investment attractiveness. Moreover, extreme temperatures caused by UHIs negatively affect sports and cultural events in a twofold way – by reducing the quality of performances and the experience and health of participants and spectators. These effects also have a direct impact on reducing the number of visitors, thereby causing additional monetary damage.

OTHER ENVIRONMENTAL IMPACTS

Aside from urban areas and their populations, the negative effects of UHIs also extend to water systems, causing changes in water balance and biological activity. Increased temperatures on the surface of roads and roofs heat rainwater, which then flows into bodies of water, raising the temperature of rivers, lakes and seas. This **has a negative impact on aquatic ecosystems and animal species that depend on these habitats**. The lack of green infrastructure elements, such as rain gardens and green roofs, further hinders the cooling and quality improvement of rainwater. The negative impact of UHIs is also reflected in water balances. During summer months, especially in dry periods, the likelihood of water shortages in urban areas increases.

UHIs contribute to an **increased risk of fire** by evaporating moisture from the soil and drying the vegetation, which facilitates the spread of fire from the periphery to the inner parts of the city.

Research shows that the increase in ambient temperature and the intensity of UHIs **negatively affect the growth and development of urban trees** by reducing their resilience to stress and shortening their lifespan. Effective management of urban green infrastructure is becoming crucial for addressing challenges associated with UHIs and preserving the environment in urban areas.

OVERVIEW OF THE METHODOLOGY FOR IDENTIFYING URBAN HEAT ISLANDS

Identifying UHIs is the process of recognizing and quantifying temperature differences that indicate UHI effects (showing significantly higher temperatures compared to surrounding rural areas), with the main goal of determining the presence and intensity of UHI effects.

There are a large number of methods and techniques for determining the extent and characteristics of UHIs in the literature, differing in terms of research goals, input data used, precision and level of complexity. **The most commonly used methods are numerical modelling, remote sensing analysis and *in situ* measurements.**

Given the need to enable the analysis of the current situation for all local self-government units at the level of the Republic of Croatia, which implies the availability of data at the national level, **a basic methodology has been proposed that combines the use of available land use data, aerial imaging and mathematical modelling of solar radiation.**

As a basic spatial data source for identifying UHIs, it is possible to use vegetation maps and land type data available in the form of the Basic Topographic Database (BTD), which was developed according to the CROTIS methodology and is under the competence of the State Geodetic Administration. This data is available upon request and mapped at a scale of 1:10,000, which is currently the only data of this type and detail available for the entire territory of the Republic of Croatia. With satellite measurements, it would be possible to map BTD categories with UHI effect categories.

The BTD contains descriptions of land cover at any point on the surface, thus determining areas with natural and built objects, and also characterizes the way humans use or interact with the land. As previously mentioned, anthropogenic influences have a primary contribution to the formation of UHIs, so it is important to conclude which anthropogenic elements and types of land use contribute more to the increased heat risk than others.

Land cover and use according to the BTD include the following categories:

- Agricultural land
- Forest area
- Tree
- Line of trees and hedge
- Other natural areas
- Economic area

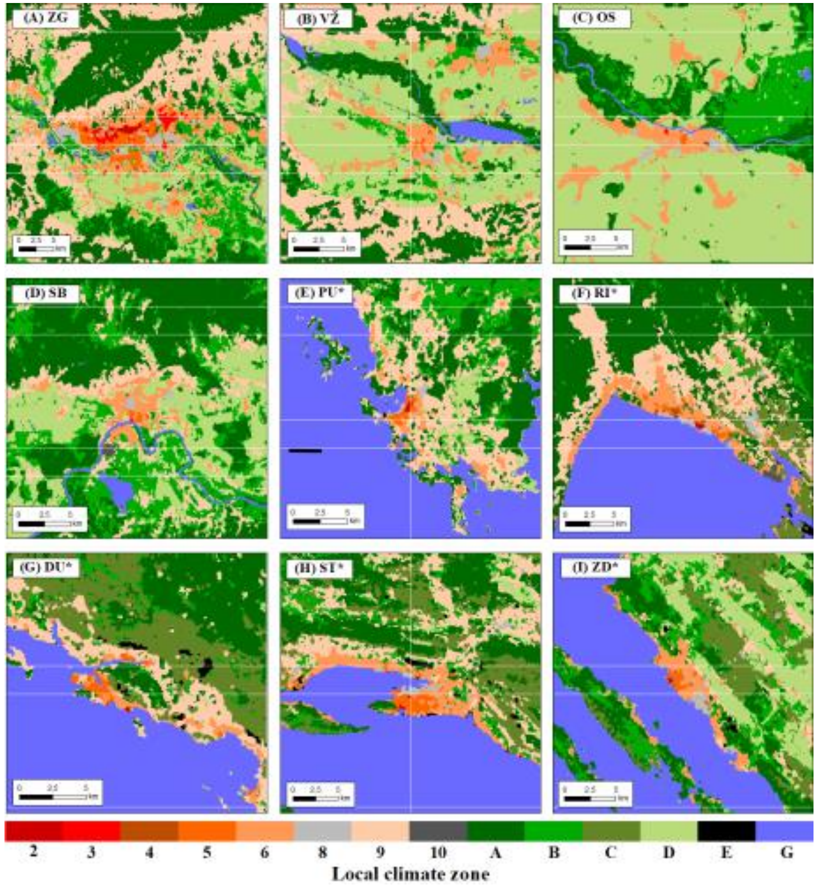
- Public areas
- Special purpose areas
- Land use.

As for aerial imagery, it is possible to use a digital surface model created from the Multisensor Aerial Survey of the Republic of Croatia, which resulted in LiDAR imagery.

By using an algorithm to calculate solar radiation, it is possible to mathematically define the amount of radiation per unit area. One possible tool is the *Modelling solar radiation* tool, which calculates the sum of direct and diffuse radiation while considering terrain topography, built-up areas, and the presence of certain elements that affect the amount of radiation.

By overlaying the land cover and land use layers (BTD) with solar radiation calculations and using GIS tools for spatial analysis, it is possible to identify areas where the UHI effect is potentially possible.

This methodology, although it **has some drawbacks such as a lower possibility of updating data and a lower level of detail**, is recommended as a basic method due to the availability of data at the level of the Republic of Croatia.



Representation of local temperature differences through local climate zones (Žgela et al. 2024)

ADDITIONAL OPTIONS AND METHODS

If other data are available at the local self-government unit (LGU) level, a more detailed identification process can be carried out. Furthermore, it is also possible to use publicly available and comparable data at EU level for those LGUs for which such data has been created. One example is the 2021 Urban Atlas Land Cover/Land Use, which operates as part of the Copernicus programme and was created for six urban areas in Croatia. In case of Urban Atlas (UA) use, surface temperature data should be linked to land use and land cover data according to UA categories. For each defined category, it is necessary to calculate the average temperature, and it is possible to use reference temperature values for individual land types (LULC), i.e. the results of the study by Žiberna and Ivanjšič (2022) who calculated the UHI effect for different LULC types in the city of Maribor, presented below:

- Complete urban areas: 4°C
- Industrial, commercial, public and military areas: 3.7°C
- Railways and associated areas: 3.3°C
- High-density unconnected urban areas: 3.1°C
- Other roads and associated areas: 2.2°C
- Medium-density unconnected urban areas: 2°C
- Unusable land: 1.9°C
- Construction sites:
- Gravel areas: 1.2°C
- High-speed transit roads and associated areas: 1.2°C
- Sports and recreation areas: 1.2°C
- Green urban areas: 1.1°C
- Airports
- Port areas
- Low-density unconnected urban areas: 0.6°C
- Arable land: 0.5°C
- Orchards
- Permanent crops (vineyards, orchards): 0.5°C
- Very low-density unconnected urban areas: 0.4°C
- Open spaces with little or no vegetation (beaches, dunes, bare rocks, glaciers)
- Complex and mixed cultivation patterns
- Herbaceous plant communities (natural grasslands, wetlands...)
- Pastures: 0°C
- Free-standing buildings: -0.2°C
- Forest areas: -1.8°C
- Wetland areas
- Water surfaces: -2.6°C

The impact of UHIs exists at a specific location within urban areas if the temperature difference between that location and the temperature outside urban areas is greater than or equal to 2°C. Accordingly, it is evident that the categories with the highest UHI effect include complete urban areas, industrial, commercial, public and military areas, high-density unconnected urban areas, railways and associated areas, as well as roads and associated areas. On the other hand, categories that actually have a mitigating effect on UHIs include water surfaces, wetlands and forest areas.

Other options depending on the availability of data for individual LGUs:

- Using microclimate models to simulate urban thermal characteristics by considering factors such as construction, green areas and urban matrix.
- Remote sensing techniques that allow data retrieval at different spatial and temporal resolutions and help to establish a spatial patterns of surface UHIs. Such data is available from various sources, for example from Landsat 8 and Sentinel 3 satellite imagery. Other data sources such as MODIS (low spatial but high temporal resolution) and ECOSTRESS (high spatial and temporal resolution) are also available.
- The *in-situ* method that includes data from official meteorological stations or a network of temperature sensors deployed throughout the city, as well as mobile measurements, for example cars or bicycles to measure air temperature at different locations in the city.
- High-resolution data collection and analysis can provide insights into the spatial distribution of surface temperature throughout the LGU. It is important to emphasize that surface temperature differs from air temperature measured by meteorological stations. It is certainly necessary to carry out an analysis of the relationship between the measured temperature (air temperature or surface temperature) and land cover and land use. For this purpose, it is possible to use local climate zones (LCZ). Given that the thermal characteristics of individual parts of the city may differ due to differences in their construction, a type of classification has been designed that takes into account the local characteristics of various parts of the city. LCZ are areas of uniform land cover, urban structure, building materials and similar human activities. Surface temperature data are publicly available for the entire world and Croatia from the 1980s to today in high spatial resolution, allowing for the determination of temporal-spatial heat changes of a particular urban area. This data is accessible on the United States Geological Service (USGS) website.
- Thermographic imaging with infrared cameras to measure temperatures locally.
- Measurements with balloons or drones to determine the temperature at different altitudes above urban areas.
- Surveys and other forms of social research provide insight into the impact that exposure of residents to the negative effects of UHIs has on their behaviour, needs, mood and quality of life.

GUIDELINES FOR MITIGATING URBAN HEAT ISLANDS

In the context of the negative impact of the expansion of built-up areas, such as increasing urban temperatures and more frequent and prolonged heatwaves, it is essential to implement measures to preserve the health of people living in cities, protect the environment and reduce energy consumption, protect the environment and preserve the health of people living in cities.

To develop high-quality, climate-neutral settlements and adapt to climate change, spatial planning and construction should include:

- Ensuring safety against risks caused by adverse effects of climate change (droughts, fires, floods, landslides).
- Ensuring water needs and sustainable management (water retention measures, rainwater reuse, deregulation of regulated watercourses, etc.).
- Ensuring green spaces with a variety of ecosystem services (planning and development of high-quality, accessible, interconnected green spaces and other nature-based solutions, including elements of blue infrastructure).
- Cooling of settlements, urban spaces and buildings (morphological design of built-up parts of settlements, ventilation, built density, the ratio between built and unbuilt spaces).
- Circular management of space and buildings (impact on reducing demand for new construction space).
- Elements of sustainable mobility (reduction in the share of motorized traffic, multipurpose use of car parks and space, efficient pedestrian and cycling infrastructure).
- Use of renewable energy sources and energy efficiency.

The following sections of the document include a proposal for guidelines to mitigate the existing and preventing the emergence of new UHIs, with a focus on green urban renewal measures, divided into the following categories:

- **Green and Blue Infrastructure**
- **Urban Planning and Design**
- **Technological Measures.**

Particular emphasis was placed on green urban renewal measures, i.e. guidelines for the development and improvement of green and blue infrastructure to be defined in the Green Urban Renewal Strategies, as explained in the final chapter of the Handbook. Furthermore, by entering spatial data on green and other open areas in the construction areas of local self-government units into the Green Infrastructure Registry, it is possible to identify areas where it is necessary to develop and increase elements of green infrastructure.

Blue and green infrastructure, Photo by: Ngoc Gabriel, Pexels

GREEN AND BLUE INFRASTRUCTURE

The development of **urban green infrastructure** (UGI) can partially mitigate the negative effects of UHIs by contributing to the resilience of urban areas to climate change. The integration of UGIs into urban planning and legislation is key to achieving this goal. Studies indicate that UGI can reduce urban temperatures by an average of 1.07°C, and in some cases up to 2.9°C, emphasizing the need for shading surfaces with tree canopies. The use of nature-based solutions can also mitigate the UHIs, but requires standardized methods to evaluate the effectiveness of the investment. It is also important to take into account the role of soil and adapt mitigation measures to the specific characteristics and purpose of individual locations. A multidisciplinary approach is crucial for the successful mitigation of UHIs and other related factors in urban spaces. Urban **blue infrastructure** is a key element in mitigating the negative effects of UHIs. Integrating blue infrastructure with urban green infrastructure creates nature-based solutions that support the complex relationships among environmental elements in urban areas. Elements of blue infrastructure, such as natural water bodies, wetlands, water transfer channels, rainwater management systems and blue roofs, have proven effective in reducing UHI effects. Through synergistic mechanisms, such as evaporative cooling and thermal energy transfer, these elements contribute to the reduction of local temperatures, creating urban areas that are comfortable for residence and outdoor activities. **Below are the general guidelines for mitigating UHI effects according to specific categories of green infrastructure typologies.**

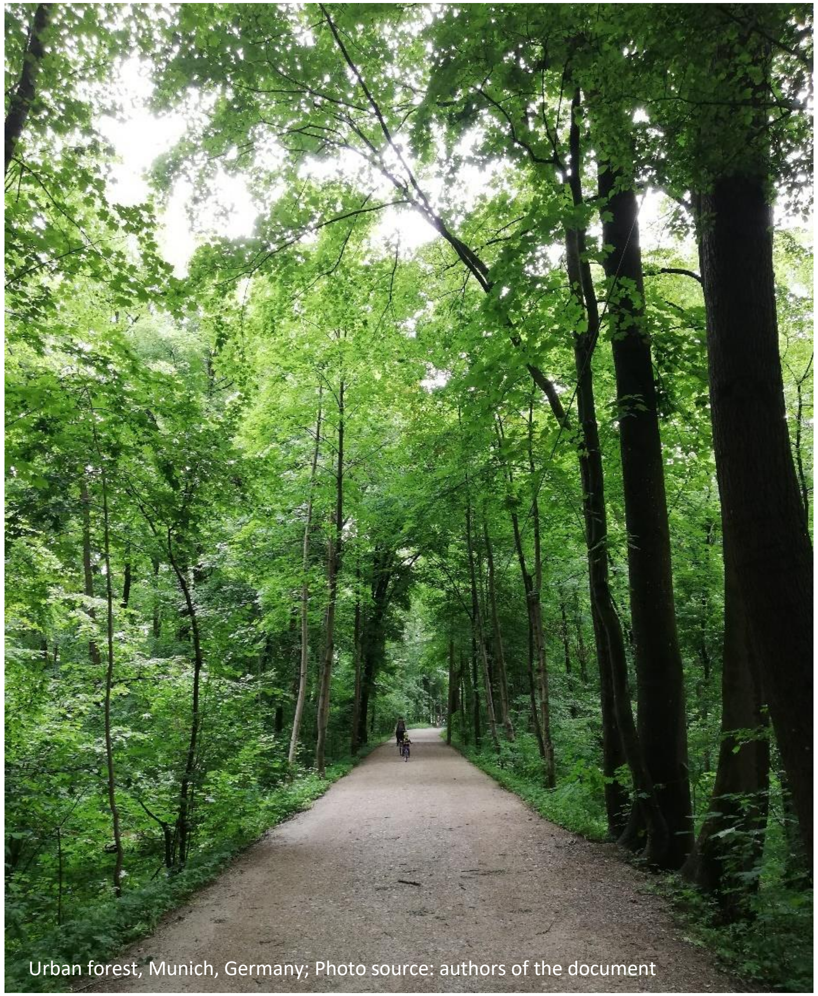
Green and blue infrastructure, Munich, Germany; Photo source: authors of the document

Urban forests, parks and gardens

Urban forests, parks and gardens, in addition to their ecological, aesthetic and recreational functions, have a significant positive impact on the processes of cooling urban spaces. Besides shading surfaces, it is very important to highlight the water cycling processes occurring in urban forests through soil water evaporation and plant transpiration. Part of the thermal energy, which would otherwise increase the temperature of the space, is thus lost by promoting these evaporation processes, thereby directly reducing the negative UHI effect at the city level.

General guidelines aimed at reducing UHI effects:

- During spatial planning, alongside orographic elements, it is recommended to utilize natural forested areas that can be expanded with urban forests to create large, continuous natural cooling corridors.
- Special attention should be paid to the protection of habitats where trees grow to avoid soil compaction due to the use of space, which can negatively affect the health of trees and other greenery, resulting in reduced shaded areas and lower evapotranspiration rates.
- Consider the possibilities of expanding the area under urban forests and forming green belts around cities.
- Enable spatial connection and intertwining within the urban space with other measures to reduce negative effects.



Urban forest, Munich, Germany; Photo source: authors of the document

Green traffic corridors

Given the large proportion of impermeable materials and heat generated by motor vehicles, roads are often the hottest open areas in cities, so it is necessary to implement temperature reduction measures along roads and within the street network. Planting trees along roads helps to reduce UHI effect by shading, i.e. lowering surface temperatures and enhancing the environmental cooling effect through evaporation and transpiration.

General guidelines aimed at reducing UHI effects:

- Select and plant species resistant to temperature increases along roads in order to enable better adaptation of urban greenery to urban environmental conditions and to improve the positive effects on reducing the negative UHI impacts.
- Connect green streets with other UGI elements in order to establish cooling and pedestrian corridors.
- Plan and design green areas along roads simultaneously with infrastructure planning to ensure favourable conditions.
- Use methods that allow for unobstructed root development and limit and prevent their negative interactions with underground infrastructure in cases of limited space for root development in the soil. Such methods ensure an adequate volume of uncompacted soil that allows the development of healthy and resilient trees, nearly unrestricted access to the area with vehicles, greater tree resistance to wind throw, temporary rainwater retention zones, etc.


Street canyons with shaded street profile, Matosinhos, Portugal; Photo by: Tadej Glažar


Landscaping of green areas along roads; Photo source: GreenBlue Urban

Squares

The lack of vegetation, that is, trees with canopies that provide shade and the possibility of creating a pleasant microclimate, is a common issue on the surfaces of squares in Croatia. This results in high temperatures in the summer months, leading to the avoidance of prolonged stays in squares and the use of such areas solely for pedestrian movement. During periods of high temperatures, squares are empty and underutilised, which contributes to the loss of the square's social function.


Green square, Tihany, Hungary; Photo by: Bence Szemerey, Pexels

General guidelines aimed at reducing UHI effects:

- In order to create a pleasant microclimate, it is important to implement greening projects for existing squares, especially in areas where passers-by could linger for longer periods.
- When designing new squares, spaces for tall greenery should be planned for.
- It is recommended to use deciduous species that create shade in the summer months and allow sunlight to pass through in the winter.
- Technical possibilities for removing parts of the paving should be considered, and in cases where this is not feasible, solutions such as planting pits should be used.
- In addition to using vegetation, it is possible to use other elements of urban design such as shading structures, materials with an impact on reducing UHI effects, artificial water elements including those with drinking water, etc.

Green constructive elements on buildings

Implementation of green roofs in building design involves covering roof surfaces with greenery that absorbs solar radiation, reduces heat penetration into buildings and, to some extent, lowers the temperature of the immediate surroundings.

Integrating green facades involves covering vertical surfaces with greenery that shades the surfaces, reduces the heat absorption of buildings, improves air quality and mitigates UHI effects.

General guidelines aimed at reducing UHI effects:

- Mandate the implementation of green roofs and facades on new buildings in accordance with the building design conditions outlined in spatial plans for areas where UHI effects have been identified.
- Conduct research on the technical possibilities for developing green constructive elements on existing buildings.
- Introduce a programme to encourage the development of green constructive elements on existing buildings.
- Develop elements for temporary water retention on the roof surface for the purpose of cooling through evaporation and the transfer of part of the thermal energy.
- Develop water elements on green roofs that provide insulation and further contribute to reducing surface temperatures.


Green constructive element, Rovinj, Croatia; Photo source: authors of the document

Integrated urban drainage systems

Rainwater treatment and drainage systems consist of infrastructure built with the purpose of sustainable management of rainwater runoff from impermeable surfaces (roads, roofs and car parks, etc.), and it is recommended to use nature-based solutions. These systems work to reduce the effects of UHIs in several ways:

- By diverting heated water, they participate in the transfer of thermal energy from built or paved surfaces to cooler soil, gravel or vegetation-covered surfaces.
- By stimulating infiltration and evapotranspiration, they reflect part of the thermal energy.
- Smaller components of green infrastructure within the rainwater treatment system, such as rain gardens, enhance cooling through evaporation and transpiration with respect to the physiological activities of plant organisms.

General guidelines aimed at reducing UHI effects:

- Integrate sustainable rainwater drainage systems in the existing green belts of the street network.
- Plan and develop sustainable rainwater drainage systems when designing new roads.
- Develop design elements for the collection, filtration, and absorption of rainwater (e.g. rain gardens) for cooling purposes, especially in areas with characteristic extremely high temperatures occurring after heavy rainfall in the summer months.
- Select species adapted to specific conditions – species that can simultaneously withstand both occasional water saturation of the soil and periodic droughts.

Construction of an integrated urban drainage system; Photo source: GreenBlue Urban

Integrated urban drainage systems; Photo source: GreenBlue Urban

Watercourse, wetland, riparian zone and surface inland waters

Natural (rivers, lakes, streams, wetlands) and artificially created water bodies (artificial lakes, reservoirs, etc.) represent an important part of blue infrastructure. They can be used for water storage, flood control, recreational purposes, but also to mitigate UHI effects. In the context of reducing UHI effects, water bodies are important because:

- They act as heat reservoirs – absorbing excess heat during the day and slowly releasing it at night, thereby moderating temperatures in the surrounding areas.
- Evaporation of water vapour from water bodies allows cooling in urban areas – part of the solar radiation is reflected when it strikes water vapour molecules, further reducing temperatures.

General guidelines aimed at reducing UHI effects:

- Explore possibilities for the restoration of regulated river watercourses.
- Maintain existing and plant new vegetation along watercourses.
- Explore the possibility of revitalizing and shaping covered streams by removing impervious materials (stream daylighting).
- Landscape watercourses as part of a network of cooling corridors.
- Design water elements with vegetation adapted to growing in water-saturated habitats in existing public spaces.
- Develop new public green areas with water elements and hydrophilic vegetation.

Rain gardens with vegetation, Lisbon, Portugal; Photo by: Tadej Glažar

Water surface in a park, Milan, Italy; Photo source: authors of the document

Selection of trees for urban areas

Given the projections of changing climatic conditions, especially during the growing season of trees' aboveground parts, in the context of selecting urban tree species, particular attention should be paid to the selection of species planned for planting along streets and other areas with a high proportion of impermeable surfaces. Such trees must be specially adapted to growth in dry conditions and intense solar radiation. Also, considering the heavy use of these areas, selected species should be resistant to the negative impacts of mechanical stress from wind impacts, which can be exacerbated by the urban canyon effect. Acknowledging these characteristics will require stepping beyond the domain of strictly native and naturalized species and seeking suitable species from the environment. Given the highly diverse microclimate conditions, significant complications can arise if only a few species are selected, so the project of incorporating greenery in urban areas should be multidisciplinary. This should include landscape architects and involve experts in urban forestry and arboriculture. When selecting climate-adapted and biomechanically suitable new species, after researching potential invasiveness in the new environment (for more information, see the EU list of invasive species)[1] and compatibility with the existing living world in the environment, and before mass planting, monitoring tests of the suitability of species in the area should be conducted. Some of the species to be considered include specially selected species for urban habitats, e.g. *Ulmus ©resista* 'New Horizon' and other resista elm cultivars, as well as *Alnus x sphaetii*, *Quercus texana* 'New Madrid', *Zelkova serrata* 'Green Vase', *Gleditsia triacanthos* 'Skyline' and cvs., *Acer rubrum* cvs., *Pyrus calleryana* 'Aristocrat', *Parotia persica*, *Jacaranda mimosifolia*, *Nyssa sylvatica*, *Fagus orientalis* 'Iskander', *Platanus orientalis* 'Minaret', etc. Among native species, it is recommended to consider using *Acer campestre* cvs., *Acer monspessulanum*, *Quercus frainetto*, *Celtis australis* (warmer continental part of Croatia), *Cercis siliquastrum*, *Corylus colurna*, *Fraxinus ornus*, *Vitex agnus-castus*, *Quercus coccifera*, and similar. Apart from the appropriate selection process, the implementation and supervision of quality should be ensured during the execution of works. The biggest challenge, besides the selection of species, currently lies in the quality control of the supplied planting material because planting inappropriately grown planting material significantly undermines the positive effects of planting and reduces the efficiency of tree interaction with the environment by reducing canopy shading. This is mainly negatively affected by high mortality rates and significantly prolonged adaptation periods of young trees to the new habitat. Further negative impacts on reducing the effectiveness of mitigating the negative UHI effects come from tree maintenance through topping, i.e., removing all thinner branches with foliage. To ensure the long-term protection of shaded areas, compensatory fees should be introduced for excessive loss of shaded areas due to aggressive and unprofessional tree maintenance practices like topping (except in cases where such interventions are prescribed as one of the remediation recommendations based on advanced biomechanical diagnostic methods in tree control or as part of maintaining special habitus forms of tree crowns).

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[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32022R1203

Solutions in cases of insufficient spatial capacity

Tree planting containers and urban planting pits are hybrid solutions when combined with elements of grey infrastructure, which can be of a permanent or temporary character.

By adequately integrating and investing in urban planting pits, it is possible to significantly improve the conditions for the growth and development of urban trees, thereby prolonging their useful life, reducing tree maintenance and care costs and significantly reducing water losses while maintaining normal physiological functions. It is recommended to use them exclusively in places where planting in ground is not possible due to existing underground infrastructure, and the recommended minimum volume of containers is 1250 litres.

Due to the limited soil volume, it is advisable to select low-growing tree cultivars with intensively maintained and shaped crowns, such as umbrella-shaped, flattened, narrow columnar or a similarly cultivated habitus form.

Due to their adaptability to space, these solutions can be used to connect green infrastructure into continuous shaded areas, which significantly enhances the ecological characteristics of the space.

Urban planting pits; Source: GreenBlue Urban

Nature-based solutions

The use of 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 the health of residents, energy savings and many more. In addition, the interaction between the environment and different types of NBS not only has a spatial component but also a temporal one, adding to the complexity of measuring and evaluating the effectiveness of investments in such solutions. For this reason, future developments in NBS integration should include the standardisation of robust methods for evaluating investment efficiency. These methods should be capable of ranking the efficiency of investments based on the specific local conditions to make well-informed decisions.

When it comes to the effectiveness of mitigating the negative UHI effects, it is essential to highlight the role of habitats, specifically urban soil, as a crucial part of the NBS system. Habitat characteristics can have a significant negative impact on water transpiration rates through aboveground plant organs, which has a double negative impact on both the UHIs and the survival and resilience of plants. Although this impact is well-known, it is often ignored due to the higher cost of establishing NBS using underground planting pits. However, compensating by planting a larger number of the same species will only worsen the situation in the long run by significantly increasing maintenance costs and promoting competition for underground and aboveground space, as well as biogenic elements and available moisture among urban greenery elements. In other words, along with the spatial component of canopy shading, it is essential to focus on the temporal component of the long-term development of shaded areas and the sustainability of urban green infrastructure development strategies.


Park with urban wetland elements, London, UK Source: GreenBlue Urban


Rainwater management, London, UK. Source: GreenBlue Urban

Island of Krk; Photo by: Niki Bonetti

PLANNING AND DESIGNING SPACES

Planning spaces that positively impact the mitigation of UHIs requires an integrated approach using different methods and strategies to achieve thermal comfort and reduce the negative effects of UHIs in urban areas.

The morphology and orientation of buildings play a key role in this process. Properly designed and oriented buildings can encourage natural airflow by creating corridors for the circulation of cooler air, thus reducing the need for energy-intensive cooling systems.

As mentioned in previous chapters, open spaces such as parks, urban forests and green roofs are also important because vegetation cools the surroundings through shading and evaporation. Urban canyon structure, street profiles, car parks and parking spaces can be optimised with nature-based solutions to reduce surface temperatures and improve thermal comfort. The use of special materials and colours further contributes to mitigating UHIs by reflecting heat and reducing absorption.

It is important to note that research has shown the effectiveness of these measures can vary depending on local conditions and urban characteristics of particular areas. Therefore, it is important to adapt space planning to the specific needs and conditions of each city.


Transparent ground floor with green atrium. Zagreb, Croatia; Photo by: Tadej Glažar


Smaller scale green corridor, Alcobaça, Portugal; Photo by: Tadej Glažar

Building morphology and orientation

The morphology and orientation of buildings are crucial for mitigating the effects of UHIs, particularly through optimising their layout and orientation to enhance natural airflow. It is of great importance to ensure green corridors in cities. The morphology of the city, including built density, building height and the Sky View Factor (SVF), is key to mitigating UHI effects. High and low SVF values combined with urban trees can help reduce the intensity of UHIs. The orientation of buildings plays a key role in mitigating the effects of UHIs by influencing airflow and reducing surface temperatures. The effectiveness of specific mitigation strategies, such as green or cool roofs, varies depending on local microclimate and urban geometry.

General guidelines aimed at reducing UHI effects:

- Plan and design buildings according to dominant wind directions in order to reduce the need for energy-intensive cooling systems.
- Plan and design buildings in such a way as to create air circulation corridors for the purpose of dispersing heat “trapped” in the built environment.
- Enhance thermal comfort for pedestrians and cyclists on paths and trails by shading and using light and permeable materials.
- Use high-albedo materials (light colours and reflective materials reflect sunlight and, consequently, heat to a higher degree), especially for roofs. In the case of facades and vertical surfaces, glare should be taken into account, so it is advisable to use matte colours.
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- Use green facades and other strategies of insulation and shading on the eastern, southern and western building facades.
- Construct new buildings at distances that allow for the development of open green spaces with trees.


Tree canopy shading, Tremp, Spain; Photo by: Philip Ackermann, Pexels


Use of high-albedo colours and materials, Island of Krk, Photo by: Niki Bonetti

Open spaces

Research has shown that shaping and enhancing street profiles, car parks and parking spaces can play a significant role in mitigating the effects of UHIs. Strategies to reduce temperature and heat circulation lead to a decrease in surface temperatures and, consequently, air temperatures, which contributes to the creation of a more pleasant microclimate in public spaces.

General guidelines aimed at reducing UHI effects:

- Explore the technical possibilities and utilise high-albedo materials (light colours) and reflective surfaces in paving street profiles and car parks.
- Plant different types of trees, shrubs and perennials in order to increase surface shading by tree canopies.
- Implement more permeable surfaces (street floor surfaces, but also surfaces within city blocks) in existing and newly planned parts of the city.
- Transform paved car parks by replacing asphalt with permeable paving solutions such as grass pavers, concrete pavers, sand and gravel surfaces with a large proportion of vegetation, etc.
- Employ urban equipment like canopies and pergolas for shading purposes.


Trees in street profile; Photo source: GreenBlue Urban

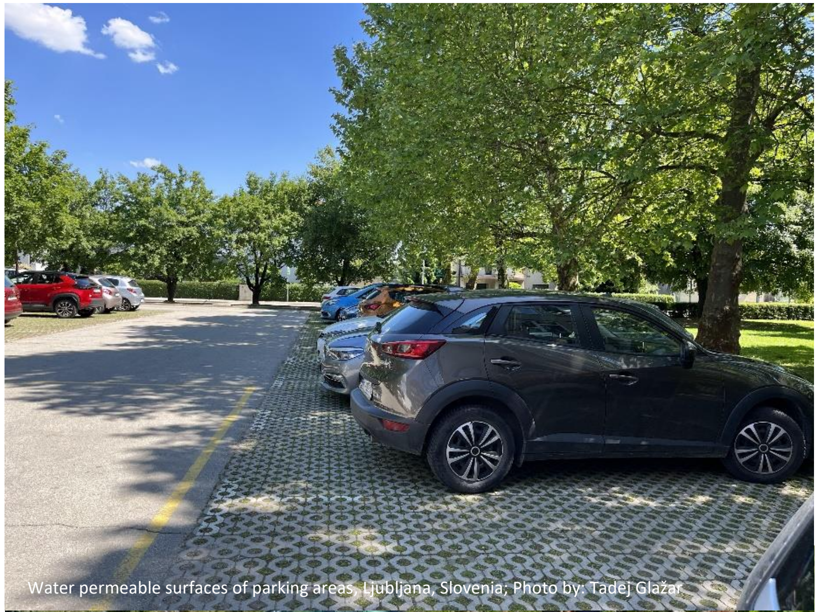

Permeable and partially paved pedestrian areas, Ljubljana, Slovenia; Photo by: Tadej Glažar

Urban equipment and materials

Urban furniture, materials and colours play an important role in reducing heat absorption and retention in urban environments and mitigating the effects of the UHIs, offering various measures to counteract its effects, which can be selectively implemented in already built public spaces (e.g. urban equipment) or systematically planned and prescribed in spatial plans (e.g. paving materials).

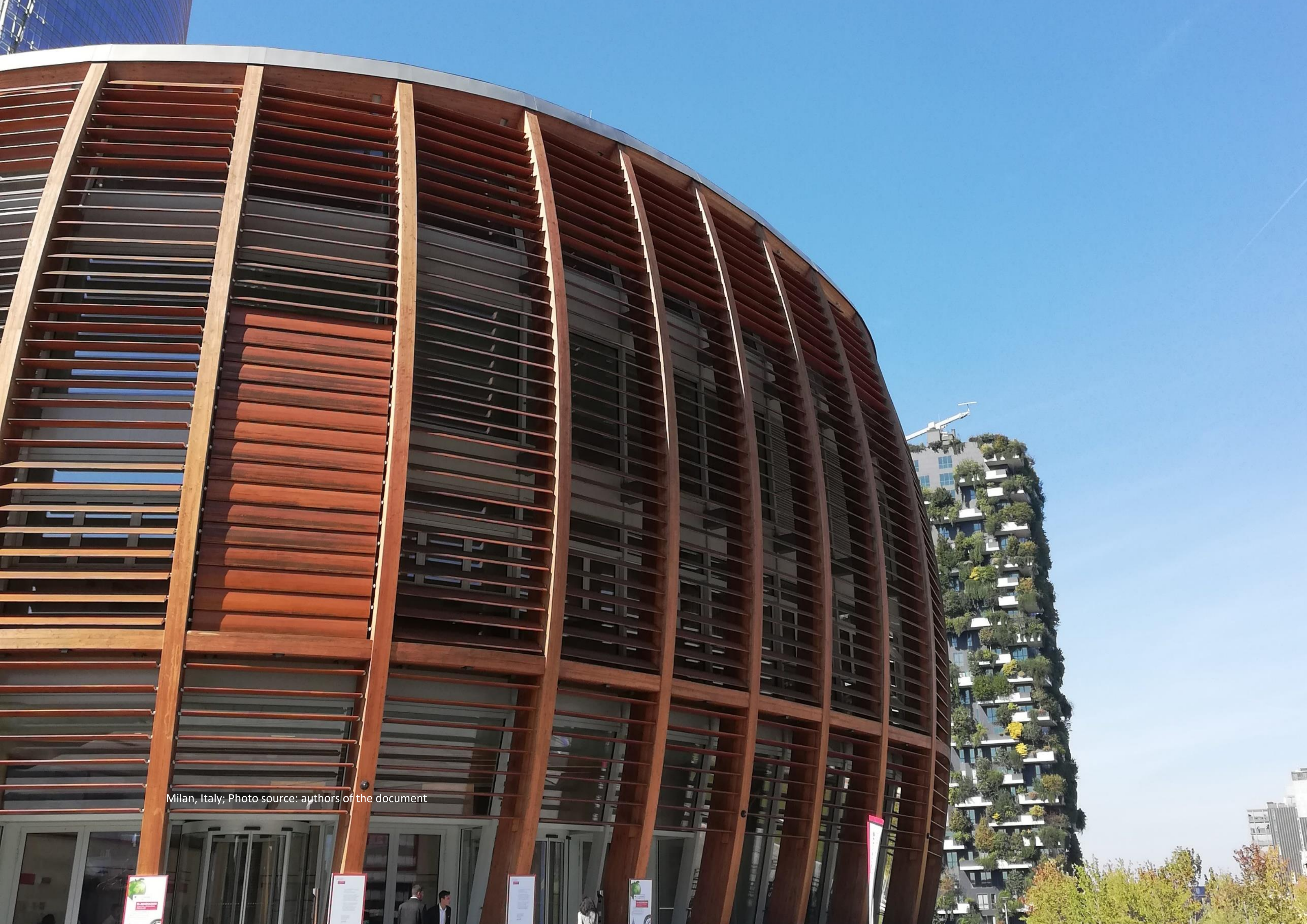
General guidelines aimed at reducing UHI effects:

- Use structures and elements for shading spaces to provide shelter from direct sunlight, reduce surface temperatures and provide relief from overheating and heat stress.
- Use urban seating equipment that includes materials with high thermal conductivity or cooling mechanisms that disperse the heat of the seating surfaces.
- Use white and light materials with high albedo in areas exposed to UHIs.
- Design water elements in public spaces such as fountains, lakes, drinking water sources, etc.
- Use urban equipment from materials with lower thermal conductivity (e.g. wood).



Water permeable surfaces of parking areas, Ljubljana, Slovenia; Photo by: Tadej Glažar

Water permeable surfaces of parking areas, Alcobaça, Portugal; Photo by: Tadej Glažar



Milan, Italy; Photo source: authors of the document

TECHNOLOGICAL MEASURES

Photovoltaic systems

In the context of UHI effects, the use of photovoltaic systems serves a dual purpose, as they can be implemented both as mitigation measures for existing UHI effects and as preventive measures against new ones.

General guidelines aimed at reducing UHI effects:

- Install photovoltaic systems for the production of clean, renewable energy, in order to reduce dependence on fossil fuels and heat emissions generated by conventional energy production systems.
- Integrate photovoltaic systems into building design to enable surface shading and reduction of solar thermal load, thereby lowering temperatures inside buildings.
- Use solar panels in public open spaces, such as public transport stops or integrated into urban equipment (shading structures, benches, etc.), which provides protection from solar radiation to users while simultaneously generating energy.

Photovoltaic systems at car park; Photo by: Kindle Media, Pexels

Effective thermal insulation and cooling technologies

Thermal insulation technologies reduce heat transfer between the interior and the exterior of buildings, thus reducing the need for heating and cooling. In urban settings, where buildings are densely clustered, effective insulation is key to mitigating UHI effects. Cooling technologies are aimed at reducing temperatures in the urban environment. In the context of mitigating UHI effects, cooling technologies play a crucial role in reducing heat absorption caused by urbanisation and human activities.


Energy-efficient building; Photo by: Magda Ehlers, Pexels

General guidelines aimed at reducing UHI effects:

- Implement energy renovation measures for buildings, given that increasing the protection of the building envelope is one of the energy efficiency measures.
- Explore the technical possibilities of using innovative insulation technologies, such as aerogels and vacuum insulation panels that offer higher levels of thermal resistance in thinner profiles, allowing for a more efficient use of space.
- Apply guidelines for constructing nearly zero-energy buildings (e.g. designing and constructing buildings with high-quality envelopes, adapting the building shape to the climate context and surrounding environment and planning the orientation of openings relative to the cardinal directions and solar exposure).
- Combine passive (using natural phenomena, such as wind and thermal physical factors) and active (reliant on mechanical or technological methods) cooling approaches.

Solar ventilation systems

Solar ventilation systems use solar energy to power fans or ventilation vents that circulate air and remove heat from buildings. By harnessing renewable energy, these systems reduce dependence on conventional energy sources and help mitigate UHI effects. Additionally, these systems can contribute to overall city sustainability by reducing carbon emissions and dependence on non-renewable resources. In this way, they can improve air quality, enhance living conditions and reduce the energy costs associated with conventional cooling methods.

General guidelines aimed at reducing UHI effects:

- Integrate solar ventilation systems in cities where cooling needs are high and sunlight is abundant.
- Combine solar ventilation systems with other passive cooling strategies, such as natural ventilation and space shading, to maximise cooling efficiency.


Solar ventilation systems, Source: Pexels, Author: Jakub Pabis

SUCCESS AND LONG-TERM MONITORING

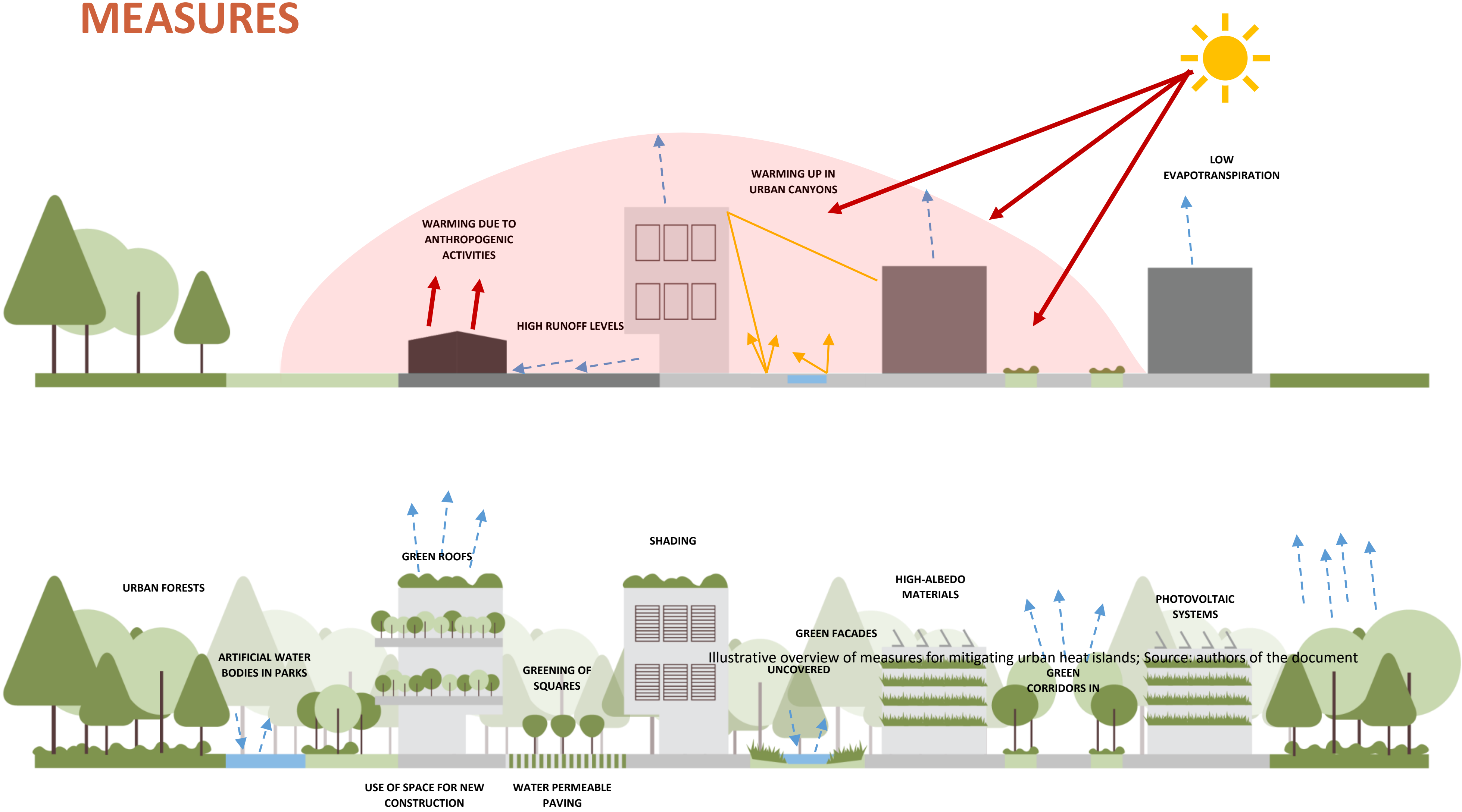
Climate change and the negative effects of UHIs pose a serious challenge in the planning of urban spaces in terms of adaptation and mitigation of negative factors. However, by using and developing appropriate methods, tools and mitigation measures, living conditions for urban populations can be significantly improved. With the aim of long-term monitoring of the effectiveness of measures, the Ministry of Physical Planning, Construction and State Assets, along with its partners, has developed the Handbook on the Application of Green Infrastructure and the Green Infrastructure Registry.

The Handbook contains 22 categories of green infrastructure that form the basis for creating the Green Infrastructure Registry and long-term monitoring of the state of urban green infrastructure in Croatian cities. Also, the typology of green infrastructure categories was used in developing the methodology for identifying UHIs.

The Green Infrastructure Registry is a new module of the Physical Planning Information System (PPIS) that will enable the entry, maintenance, and analysis of data on green infrastructure for urban areas in the Republic of Croatia, and the entry of spatial data from the Green Urban Renewal Strategies. Therefore, it represents an important step towards sustainable, efficient and resilient urban planning.

Milan, Italy; Photo source: authors of the document

IMPLEMENTATION OF MEASURES



Illustrative overview of measures for mitigating urban heat islands; Source: authors of the document

In order to mitigate the effects of UHIs, it is important to **implement measures in spatial planning and construction processes** and to use available instruments that enable a comprehensive mitigation approach. When developing spatial plans (or their amendments), it is necessary to adapt the purpose and use to the climate context and to define measures for the most critical parts of the settlement, that is, those where the presence of UHIs has been identified and mapped. It is also important to take into account the spatial characteristics that contribute to the creation of UHI effects when planning new interventions and to strive to prevent them. This could include:

- The morphology and orientation of individual buildings and their mutual relationship for the purpose of forming cooling corridors, which can be defined by the location of the building, the construction of the building plot, the coefficient of construction, the height and the number of floors.
- More detailed prescribing of typology, proportions and shape of buildings in the context of thermal protection effectiveness.
- The use of materials of high energy efficiency, colours and types of materials to reduce UHI effects, which can be defined by the conditions for the design of the building or by prescribing construction products and their properties.
- Implementation of nature-based solutions (e.g. green roofs and facades) in parts of settlements with higher construction density by defining the conditions for the design of buildings.
- Increasing the share of green areas and canopy coverage by prescribing the conditions for the arrangement of spatial interventions (defining the share of natural terrain that can affect the creation of a pleasant microclimate).
- Development of diverse public green areas and their interconnection into the green infrastructure system by prescribing specific measures for areas with special constraints.
- Integrated consideration and implementation of UHI mitigation measures in areas suitable for comprehensive renovation by prescribing urban rehabilitation and urban transformation measures.
- Defining measures for the management of watercourses and other water surfaces in the context of green infrastructure.
- Inclusion of international standards such as the “3-30-300” rule, which involves having a view of three visible trees from home, workplace or learning place, at least 30% of area shaded with tree canopy, and residence within 300 metres of a large and well-planned public green space.

Green Urban Renewal Strategies (GURS)[2] are strategic bases of significance for local self-government units, relating to the achievement of goals in green infrastructure development, integration of NBS solutions, improvement of circular management of space and buildings, achievement of energy efficiency goals, adaptation to climate change and strengthening resilience to risks. Given the above, they represent an important tool for identifying and defining UHI mitigation measures. In the new version of the *Guidelines for the Development of Green Urban Renewal Strategies*, it is proposed to include an additional chapter in the GURS focusing on UHIs. In the aforementioned chapter of the GUR Strategy, it is necessary to identify the most critical parts of cities and municipalities, that is, those where the impact of UHIs is greatest, and to define specific measures and projects for the development and improvement of green and blue infrastructure. Analytical results of UHI identification with graphical representations should be included in the analytical part of the GUR Strategy, and based on the results, measures and projects should be defined whose implementation in spatial plans and direct implementation will ensure favourable microclimatic conditions for residents and visitors.

By developing the GUR Strategy and entering data on existing green and other open areas into the new module of the Physical Planning Information System, that is, the Green Infrastructure Registry, decision-making on spatial planning aimed at strengthening resilience to risks and adapting to the negative impacts of climate change, such as UHIs, will be facilitated. Local self-government units will be responsible for data entry into the Green Infrastructure Registry, with data entry foreseen according to 22 typologies of planned open spaces, green and blue areas that make up green infrastructure in built-up areas. In addition to spatial plans and GUR Strategies, other available instruments and tools are important in the context of mitigating the negative effects of UHIs and achieving climate resilience in urban areas, such as:

- Demographic projections, forecasts and analyses (expert studies)
- Modelling scenarios for predicting the effects of climate change, tools for modelling overheating, noise and air quality, etc.
- Instruments for public involvement and participatory management of urban spaces (workshops, focus groups, survey questionnaires and research)
- Economic instruments (co-financing projects through programmes such as Competitiveness and Cohesion 2021-2027, National Recovery and Resilience Plan, etc.)
- Project management tools (coordination of multiple projects and integrity of individual projects)
- Education, continuous professional development and awareness-raising (for administrators, decision-makers and the general public).

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[2] https://mpgi.gov.hr/graditeljstvo-98/obnova-od-potresa-privatnih-zgrada-i-kuca-10668/financijska-sredstva-za-obnovu/nacionalni-plan-oporavka-i-otpornosti-inicijativa-obnova-zgrada/izrada-strategija-zelene-urbane-obnove/14837

CONCLUDING REMARKS

Global processes of increasing environmental temperatures are one of the important factors driving the adaptation processes of all living beings. Urban spaces are created by human modifications of the environment and, in the context of warming, they are characterized, among other things, by the negative effects of Urban Heat Islands (UHIs). The negative effect of UHIs is intensified by the expansion of urban spaces and the increase in the density of built structures with impermeable surfaces, leading to higher temperatures of the urban environment. Therefore, it is recommended to initiate adjustments in urban spaces to foster a stimulating and healthy urban environment.

Effective mitigation of the negative consequences of UHIs relies on:
1. identifying and evaluating UHI intensity and considering the wider context of the area (spatial, climatic, socio-economic, etc.)
2. determining priority areas for UHI mitigation by defining measures in GUR strategies, their implementation through spatial plans and utilising information from available tools, primarily the Green Infrastructure Registry, etc.
3. evaluating the effects of implemented measures and solutions.

With the aim of successfully mitigating the negative consequences of the UHIs, the Ministry of Physical Planning, Construction and State Assets constantly carries out activities to support local self-government units in the preparation and implementation of specific solutions. Therefore, it is recommended to monitor the planned activities, calls and support on the Ministry's website[3] with the aim of successful implementation of effective solutions.

It is important to emphasize that this Handbook offers a set of measures that are currently considered as examples of good practices for mitigating UHI effects. However, it is recommended to stay updated with professional research and method development, adapting decision-making and solutions to new findings, all with the aim of maintaining high efficiency in mitigating the negative effects of UHIs.

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[3] https://mpgi.gov.hr/eu-sufinanciranja/10524

BASIC CONCEPTS FOR UNDERSTANDING THE URBAN HEAT ISLAND

Albedo – The reflection of light from a surface. It is measured on a scale from 0, representing a black body that absorbs all incident radiation (heat), to 1, representing a body that reflects all incident radiation.

Atmospheric Urban Heat Island – The temperature differences in the atmospheric layer above an urban area compared to the surrounding rural areas.

Evaporation – The process occurs when a liquid on the surface turns into a gas or vapor.

Evapotranspiration – The loss of water from the Earth's surface through the evaporation of moist surfaces and transpiration through plant pores.

Surface Urban Heat Island – The temperature differences at the interface of the outdoor atmosphere with the solid materials of the city and the equivalent rural air to ground interface.

Level of Global Warming – The extent of global temperature increase by the end of the 21st century.

The Green Infrastructure Registry– A new module of the Physical Planning Information System (PPIS) that will enable the entry, maintenance, and analysis of data on green infrastructure for urban areas in the Republic of Croatia, and the entry of spatial data from the Green Urban Renewal Strategies.

Soil surface temperature - The temperature of the ground in direct contact with the atmosphere. This refers to the temperature measured on the surface of the soil or land, not the air above it.

Transpiration – Excretion of water from a plant in the form of water vapour on surfaces bordering the atmosphere, by which plants significantly contribute to the circulation of water in the global ecological system. The larger the transpiration surface and the lower the atmospheric water vapour saturation, the greater the potential transpiration.

Land use / land cover – Different categories used to classify and describe the ways in which land is used and the physical covers present on the Earth's surface. Common LULC types include urban areas, forests, agricultural land, water bodies, etc.

Urban Heat Island (UHI) – An urbanized area that is significantly warmer than its rural surroundings due to built infrastructure and anthropogenic activities.

Water balance - Water balance is an accounting of the inputs and outputs of water. The water balance of an area can be determined by calculating the input, output, and storage changes of water at the Earth's surface. The major input of water is from precipitation and output is evapotranspiration.

LITERATURE AND SOURCES

Photo sources: Pexels, GreenBlue Urban, Niki Bonetti, Tadej Glažar and other authors of the document

Adams QH, Chan EMG, Spangler KR, Weinberger KR, Lane KJ, Errett NA, Hess JJ, Sun Y, Wellenius GA, Nori-Sarma A,2023. Examining the Optimal Placement of Cooling Centers 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.

Herdt AJ, Brown RD, Scott-Fleming I, Cao G, MacDonald M, Henderson D, Vanos JK, 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.

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.

Arias PA, Bellouin N, Coppola E, Jones RG, Krinner G, Marotzke J, Naik V, Palmer MD, 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., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press

Bednar-Friedl B, Biesbroek GR, Schmidt DN, Alexander P, Børsheim KY, Carnicer J i sur Europe: from Chapters and Cross-Chapter Papers. In Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, 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

Black-Ingersoll F, de Lange J, Heidari L, Negassa A, Botana P, Fabian MP, Scammell MK. 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

Boras M, Herceg-Bulić I, Žgela M, Nimac I, 2023. Temperature characteristics and heat load in the City of Dubrovnik. Geofizika, 39(2). 259-279. https://doi.org/10.15233/gfz.2022.39.16

Bouyer, J., & Musy, M. (2009). MITIGATING URBAN HEAT ISLAND EFFECT BY URBAN DESIGN: FORMS AND MATERIALS.

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.

Brocherie F, Girard O, Millet GP. Emerging Environmental and Weather Challenges in Outdoor Sports. Climate. 2015; 3(3):492-521. https://doi.org/10.3390/cli3030492

Cedilnik R, 2015. Določanje temperature tal iz satelitskih posnetkov Landsat: Magistrsko delo [Thesis, University of Ljubljana, Faculty of Civil and Geodetic Engineering]. https://repozitorij.uni-lj.si/IzpisGradiva.php?id=32772.

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.

Cheela VRS, 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.

Chmielewski, F. M., & Rötzer, T. (2001). Response of tree phenology to climate change across Europe. Agricultural and Forest Meteorology, 108(2), 101-112.

Chow WTL, Salamanca F, Georgescu M, Mahalov A, Jeffrey M. Milne, Ruddell BL, 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

Copernicus Land Monitoring Service. (b. d.-a). Mapping guide—Urban Atlas Land Cover/Land Use and Street Tree Layer 2012 and 2018. Pridobljeno 20. februar 2024, s https://land.copernicus.eu/en/products/urban-atlas/urban-atlas-2018.

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.

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

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.

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.

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.

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 [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 907–1040, doi:10.1017/9781009325844.008.

European Commission, Directorate-General for Environment, Commission Implementing Regulation (EU) 2022/1203 of 12 July 2022 amending Implementing Regulation (EU) 2016/1141 to update the list of invasive alien species of Union concern,Official Journal of the European Union, pristupljenno: 13.05.2024.

European Environment Agency. (b. d.). CORINE Land Cover 2018 (vector/raster 100 m), Europe, 6-yearly [dataset]. preuzeto 11. ožujak 2024, https://land.copernicus.eu/en/products/corine-land-cover/clc2018

European Environment Agency. (b. d.). Urban Atlas Building Height 2012 (raster 10 m), Europe—Version 3, Oct. 2022. EEA geospatial data catalogue. Pridobljeno 12. marec 2024, https://sdi.eea.europa.eu/catalogue/copernicus/api/records/42690e05-edf4-43fc-8020-33e130f62023

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.

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.

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

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.

Holz I, Franzaring J, Böcker R, Fangmeier A, 2011. Eintrittsdaten phänologischer Phasen und ihre Beziehung zu Witterung und Klima; LUBW: Karlsruhe, Germany.

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.

Holz I, Franzaring J, Böcker R, Fangmeier A, 2011. Eintrittsdaten phänologischer Phasen und ihre Beziehung zu Witterung und Klima; LUBW: Karlsruhe, Germany.

Hooyberghs H, Lauwaet D, Lefebvre W, Driesen G, Van Looy, S., Wouters, H, ... & 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.

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.

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

Ivajnšič D, Donša D, Grujić VJ, Pipenbaher N.(2022. Primeri prostorskih analiz vplivov podnebnih sprememb: Monografija v okviru projekta Preprečevanje toplotnega stresa v urbanih sistemih v luči podnebnih sprememb (ARRS J7-1822). V Univerzitetna založba Univerze v Mariboru. Univerzitetna založba Univerze v Mariboru. https://doi.org/10.18690/um.fnm.8.2022.

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.

Landezine – Landscape Architecture Forum. https://landezine.com/

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.

Leal Filho W, Wolf F, Castro-Díaz R, Li C, Ojeh VN, Gutiérre N, Nagy GJ, Savić S, Natenzon CE, Al-Amin AQ, 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.

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.

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.

Loh N, Bhiwapurkar P, 2021. Urban heat-mitigating building form and façade framework. Architectural Science Revie 65(10): 1–15. https://doi.org/10.1080/00038628.2021.1924610.

Manoli G, Fatichi S, Bou-Zeid E, Sun T, Masselot P, Huang WT 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.

Magli 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.

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

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.

Mohan M, Kikegawa Y, Gurjar, B R, Bhati S, Kolli NR, 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

Moosavi F.H., & Mahdavi, M. (2017). Reducing Heat And Urban Discomfort With Water.

Mora C, Dousset B, Caldwell IR, Powell FE, Geronimo RC, Bielecki CR, Counsell CWW, Dietrich BS, Johnston, ET, Louis LV, Lucas MP, McKenzie MM, Shea AG, Tseng H, Giambelluca TW, Leon LR, 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

Morini E, Castellani, 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.

Mossel C, Ameling L, Zaradich M, Woody MA, 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.

MPGI - Ministarstvo prostornoga uređenja, graditeljstva i državne imovine, 2019, Smjernice za zgrade gotovo nulte energije. Zagreb 2019. https://mpgi.gov.hr/naslovna-blokovi/o-ministarstvu-15/djelokrug/energetska-ucinkovitost-u-zgradarstvu/smjernice-za-zgrade-gotovo-nulte-energije/10502

MPGI - Ministarstvo prostornoga uređenja, graditeljstva i državne imovine (2021). Program razvoja zelene infrastrukture u urbanim područjima za razdoblje 2021. do 2030. godine. Zagreb, 2021. https://mpgi.gov.hr/UserDocsImages/dokumenti/EnergetskaUcinkovitost/Program_razvoja_zelene_infrastrukture_do_2030.pdf

Oberoi, A, Mullan, K, 2019. Urban Heat Island and Residential Property Values: A Systematic Review. Sustainability, 11(6): 1633.

Oke TR, Mills G, Christen A, Voogt JA, 2017: Urban Climates. Cambridge University Press, Cambridge. https://doi.org/10.1017/9781139016476.

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.

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.

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.

Pratiwi SN, 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.

Priyadarsini R, Wong N, Cheong KWD,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.

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.

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.

Rendana M, Idris WMR, Rahim SA, i sur 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

Roloff A, 2013. Bäume in der Stadt. 110, Ulmer Verlag: Stuttgart, Germany.

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.

Rosso F, Golasi I, Castaldo VL, Piselli C, Pisello AL, Salata 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

Ruiz-Aviles V, Brazel A, Davis JM, 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.

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.

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.

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.

Sen S, Fernandèz JPRM-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.

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.

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.

Smid M, Russo S, Costa AC, 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.

Steeneveld GJ, Koopmans S, Heusinkveld BG, Theeuwes NE, 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.

Stewart ID, Oke TR, 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

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.

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.

Alberto Muscio •Sergio Takebayashi H, Moriyama M, 2009. Study on the urban heat island mitigation effect achieved by converting to grass-covered parking, Solar Energy 83(8):1211-1223. https://doi.org/10.1016/j.solener.2009.01.019.

Taleghani M, Swan W, Johansson E, Ji Y, 2021. Urban cooling: Which 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.

Teruaki I, 2006. Structure and Function in Urban Landscape in term of reduction of Heat island by green space.

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

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.

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

Unger J, Sümeghy Z, Zoboki , 2001. Temperature cross-section features in an urban area. Atmospheric research, 58(2), 117-127. 10.1016/S0169-8095(01)00087-4.

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

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

Wouters, H., i sur, 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.

Xu L, Wang J, Xiao F, El-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

Yuan C, Mei S, He W, Adelia AS, 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, EMS2021-1, https://doi.org/10.5194/ems2021-1.

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.

Zaninović K, 2003. The influence of meteorological parameters on the acute neurovegetative disability, ECAM 2003, Roma, 15. –19. 9.

Zaninović K, Gajić- Čapka M, 2008. Klimatske promjene i utjecaj na zdravlje, Infektoloski Glasnik 28(1): 5–15.

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. Klimatski atlas Hrvatske / Climate atlas of Croatia1961–1990., 1971–2000. Državni hidrometeorološki zavod / Meteorological and Hydrological Service, Zagreb, p. 200.

Zellweger F, De Frenne P, Lenoir J, Vangansbeke P, Verheyen K, Bernhardt-Römermann M, i sur, 2020. Forest microclimate dynamics drive plant responses to warming. Science 368(6492):772-775. https://doi.org/10.1126/science.aba6880.

Zhao L, Oleson K, Bou-Zeid E, *i sur* 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.

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.

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.

Žgela M, 2018. Urbana klimatologija—Primjer toplinskog otoka grada Zagreba. Geografski horizont, 64(2), 33–42. https://hrcak.srce.hr/220514.

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.

Žiberna I. 2022. Sezonski režim površinskega mestnega toplotnega otoka v Mariboru. V D. Ivajnšič, Primeri prostorskih analiz vplivov podnebnih sprememb: Monografija v okviru projekta Preprečevanje toplotnega stresa v urbanih sistemih v luči podnebnih sprememb (ARRS J7-1822). Univerzitetna založba Univerze v Mariboru. https://doi.org/10.18690/um.fnm.8.2022.