Local Climate Zoning Interaction on Land Surface Temperature Determination - City of Split Case Study

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ABSTRACT:

In the Split City area, with an air distance of approximately 18 km, the survey of land surface temperature (LST) and urban heat islands (UHI) was detected. It also shows how local geomorphology, especially the density of urban areas (especially densely built high-rise buildings and urban canyons) and the amount of greenery and water surfaces, affect the UHI of the observed area. The paper uses a known method of classifying local climatic zoning (LCZ) and its coincidence with the zones of the highest urban temperatures. The paper highlights the critical areas and suggests possible solutions to reduce the UHI.

1. Introduction

According to Columbia University project, the total area of cities occupied 2.7% of the Earth's land surface, and about 51.45% of the world's population lives in that area (URL 1). In Europe, the situation is even more drastic (Fig 1). Certain studies estimated that the urban population will increase from 50% to 68% by 2050 (UN, 2018).

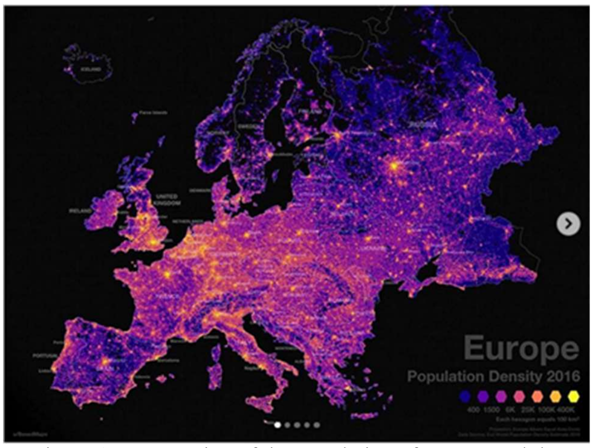

Figure 1. Presentation of the population of Europe and the south-eastern part of Europe from 2016 (URL 2)

The predominant materials in urban areas are concrete, asphalt, or brick, which heat up differently than the natural materials of soil, water, or vegetation, and can increase the temperature by 12ºC or more compared to the surrounding rural area (Fig 2), resulting in urban heat islands (UHI). UHIs significantly affect people's health, energy consumption, and the economy in general (Stewart and Oke, 2012).

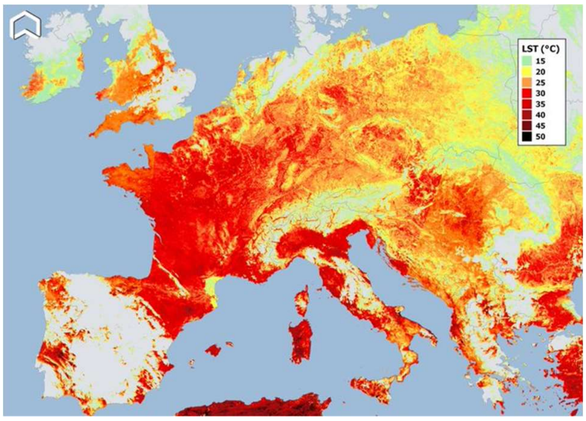

Figure 2. Land Surface Temperature map collected by Copernicus Sentinel3 on Sept. 6 2021 in Europe (URL 3)

It has been a proven relationship between human activity and UHI intensity. The causes of the occurrence of UHI can generally be divided into two types: ***locational and meteorological causes*** (geographic location, global climate weather, and local weather) that we cannot influence and ***anthropogenic factors*** that can be reduced or mitigated: city form, city size, and human activities. The causes of city form are the ones we can influence; the most, and those are (1) loss of natural vegetation and their replacement with vapor impermeable materials that cause a decrease in evapotranspiration, a decrease in humidity and dryness of urban areas; (2) dominant urban building materials (asphalt or concrete), which have a high albedo (ratio of incoming and reflected energy) that increases the storage of thermal energy; (3) parts of urban geometry, e.g. urban canyons, are created due to dense construction and prevent the natural flow of air, absorb and store large amounts of solar energy and do not allow cooling during the night, therefore pockets of hot air are formed in these places; (4) car exhausts, industry, and cooling devices also contribute to the increase in temperature, especially LST which

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creates UHI (Wai et al., 2022; Duplančić Leder et al., 2016) (Fig3).

Many studies deal with mitigating the effects of UHI in urban areas, improving urban resilience, and reducing anthropogenic impact: UHI effect reduces vegetation and water surfaces in general. On the other hand, a rural area does not have the UHI appearance because of high evapotranspiration and large shaded areas created by vegetation and water areas (Wai et al., 2021).

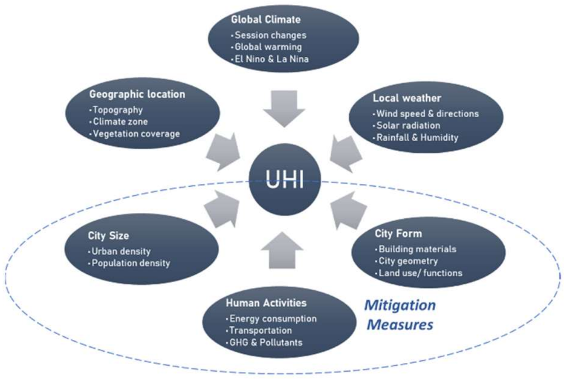

Figure 3 The main Factors that cause the Urban Heat Island Effect (according to Wai et al., 2022).

The majority of urban areas have become overpopulated and overbuilt, therefore the number of green spaces in cities has decreased (Kemarau and Eboy, 2021), causing changes in the temperature balance. UHI is mostly influenced by the physical properties of dominant building materials (albedo or solar energy reflection coefficient) (Babić et al., 2012); High buildings create canyon effects, which increase heating surfaces that absorb heat and block the flow of air masses that cool the space (Duplančić Leder et al., 2016). The air and land heating and UHI creation also depend on land usage, so the temperature warming differs by the type of urban zone (residential zone, industrial zone, tourist zone, suburban zone with vegetation and parks) (Fig 4). Industrial zones may be as much as 7 °C warmer than the surrounding areas.

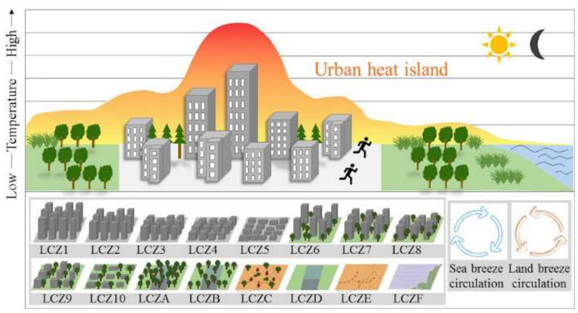

Figure 4. Urban heat islands (according to URL 4)

There are two types or two layers of UHI: the ***surface layer*** and the ***atmospheric layer*** (Oke, 1997; Liu et al. 2020) (Fig 5). Surface heat islands have a higher land surface temperature in urban areas compared to temperatures in the surrounding areas. Atmospheric heat islands, characterized by warmer air in urban areas compared to rural areas, can be divided into two separate layers: the canopy layer, which extends in urban areas upwards from the ground surface to the top of trees or buildings, and the border layer extending upwards from the canopy layer to as much as one mile above the ground level.

Surface land and air temperature are important factors in urban climatology studies. Land and atmospheric heat islands differ greatly from one another and are present during the day and night. They are most intense in summer with a daily peak intensity of 3 - 8 °C and a nightly peak of 8 - 12 °C (Yang et al., 2022).

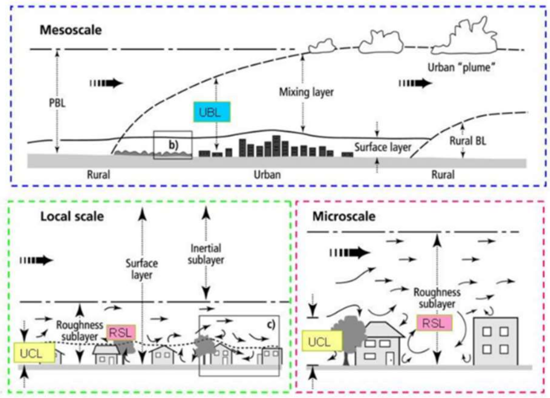

Figure 5. Thermal layers according to Oke (1997)

The world's major capital cities have been studying their urban spaces for a few decades, therefore they use new materials and increase vegetation cover whenever possible. Thus they are preparing for climate change by adapting and changing their environment (Wu & Ren, 2018). On the contrary, there are very few studies of thermal islands for the cities of the Republic of Croatia (Žgela et al., 2024). Duplančić Leder et al., (2016) analysed Landsat thermal satellite images of the city of Split and showed the increase in LST at the beginning of the millennium and five years later.

The paper aims to show how local geomorphology influences micro-climate changes in the land surface temperature observed at the City of Split area. Local climate zoning (LCZ) was used in the study, which coincides with the zones of the highest urban temperatures, thus indicating critical points and proposing possible solutions for reducing UHI. The research results should inform planners about the most vulnerable and critical thermal areas, and provide them with measures for the reduction of surface and air temperature.

2. STUDY AREA

2.1 City of Split Study Area

The City of Split is one of the oldest and also the second largest city in the Republic of Croatia. The city is the economic, administrative, transport, and tourist center of the eastern part of the Adriatic coast. In this study, we focused on the Split urban city area (yellow area) shown in Figure 6. The air distance between the most distant points of the city of Split is approximately 18 km. The City area is 22 km^2, and its suburban communities occupy four times the surface area of 80 km^2.

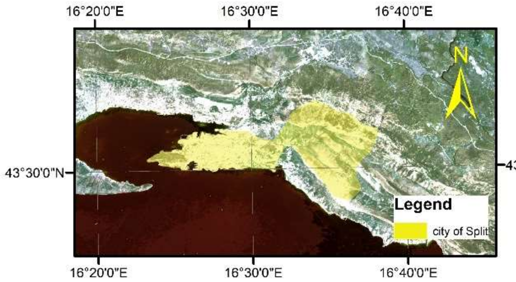

Figure 6. Split city areas.

Split is situated on a peninsula between the eastern part of the Gulf of Kaštela and the Split Channel. The Marjan hill (178 m), rises in the western part of the peninsula. The Kozjak (779 m) and Mosor (1,339 m) ridges on the north (Fig 7) protect the city from wind bura (northeast wind) and separate it from the hinterland.

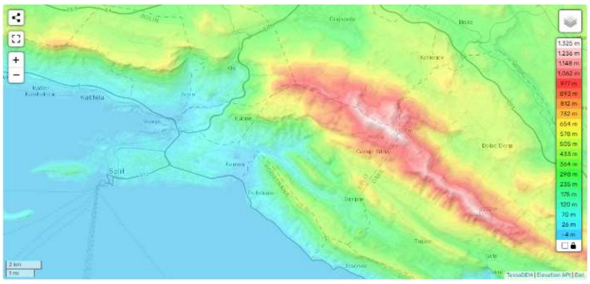

Figure 7. Elevation map of the city of Split area.

In the last two population censuses in the city of Split, a population decline of about 5% was observed, while in the last census, a population decline of about 10% was observed (Fig 8). In contrast, the agglomeration of Split has a constant small population increase. According to the 2021 census, the city of Split had 160,577 inhabitants, 59,947 households, and 77,309 apartments, which means that there are at least 17,362 empty housing units on its territory (URL 4), that is, almost every fourth apartment is empty. Most of the empty apartments are used as tourist apartments and are used occasionally, and about 10% of the empty apartments are not used at all. The city has an inconvenient geographical location and insufficient space for urban expansion. About 700 residential units are built annually, mostly interpolations, because of which the city loses large amounts of green areas, which ultimately results in UHI zones.

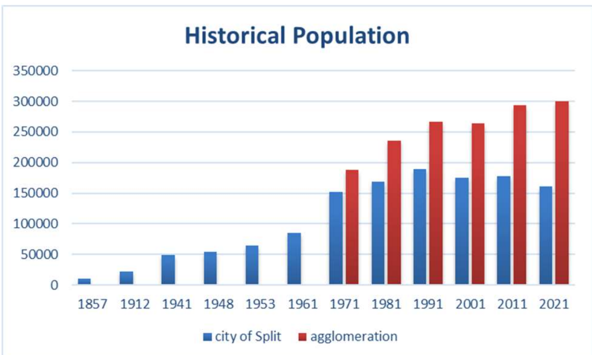

Figure 8. City of Split: Population trends 1857–2021 (according to URL 4)

The Copernicus Land Monitoring Service Urban Atlas result is the Land Use Land Cover (LCLU) information of the urban Split area. Residential zones are shown in red and industrial areas in purple (Fig 9).

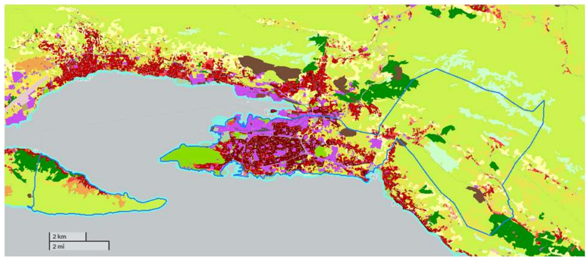

Figure 9. Copernicus Land Monitoring Service Urban Atlas Land Use Land Cover 2018 - (vector, raster 100 m) according to URL 5

The population density is 2244/km² (rising to 7499/km² in the city center) (URL 4). The Split economy has been growing at the rate of about 6 %, therefore the city is becoming the fastest-growing economy in the Republic of Croatia, especially in tourism. In the last few years, the number of tourist visits to the city has doubled compared to the number of inhabitants in the city core. The sudden growth in economic activity is also reflected in urban area climate change.

2.2 The climate of the city of Split

Split has a Mediterranean climate (Csa) in the Köppen climate classification. The climate is characterized by warm and moderately dry summers (with an average air temperature ranging from 21.5° to 25.9 °C) and mild, wet winters (with an average air temperature ranging from 7.9° to 10.7 °C). The mean annual air temperature is 16.3°C. The average annual rainfall is more than 780 mm. January is the coldest month with an average temperature of 7.9°C. November is the wettest month, with a precipitation total of nearly 113 mm and 12 rainy days. July is the warmest with an average temperature of 25.9°C and the driest month, with a precipitation total of around 26 mm (Fig 10).

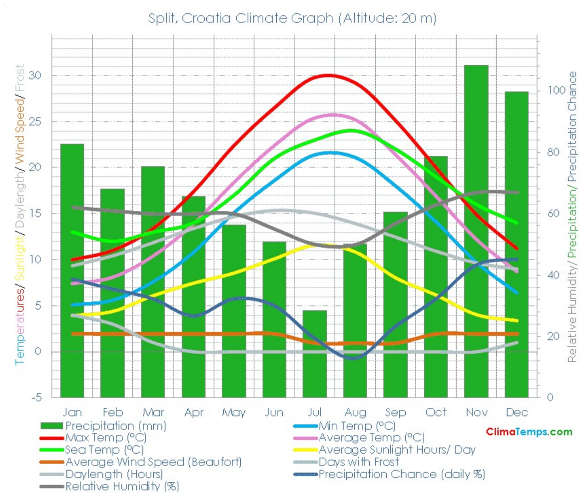

Figure 10. Climate data for Split (Marjan Hill, 1971–2000, extremes 1948–2019) (URL 6)

The lowest temperature measured on 23 January 1963 was -9 ºC, while the highest temperature of 38.6 ºC was measured on 5 July

1950. An annual average of days with precipitation is 122 days (URL 6).

Split receives more than 2,600 sunshine hours annually. July is the hottest month, with an average high temperature of around 30 °C. Dominant winds in the winter are bora and sirocco, blowing with a frequency of 35 to 55 % per year (URL 6), while mistral is the dominant wind in the summer period. The Adriatic Sea is a natural water reservoir, with a sea temperature ranging from 10 to 26 °C, and it is also the most important climate regulator in the wider area (CMHS, 2017).

3. MATERIALS AND METHODS

3.1 Local Climate Zoning (LCZ) classification method

One of the methods that clearly shows how urban geomorphology affects the thermal characteristics of the area is the classification system of local climate zones (LCZ). The method proposed by Oke and Stewart (2012), gave guidelines for application and described certain types of local climate zones, i.e. how differences in the construction of certain city parts (zones) affect LST (Stewart et al., 2014). The advantage of this classification is the simplicity and universality of application on any urban surface.

This classification method determined seven types of natural cover (from A to G, they are lined up: dense forest, sparse forest, bushes, low vegetation, bare rocky and earthy soil and water) and ten types of built-up land (from 1 to 10, they are lined up: densely built high-rise, medium-rise and low-rise buildings, medium-densely built high-rise, medium-rise and low-rise buildings with a moderate amount of greenery, densely and sparsely built low-rise buildings, extremely sparse construction, industrial area; Figure 11) (Johnson and Jozdani, 2019). The boundaries of individual LCZ are most often defined using satellite or aerial images of an individual area where they can be demarcated.

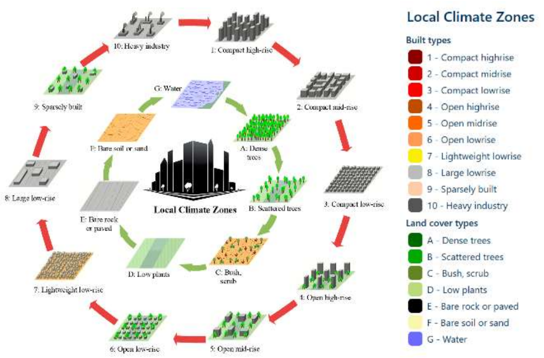

Figure 11. Local climate zone classifications, based on Stewart and Oke (2012)

Local Climate Zone (LCZ) Generator is a web application whose goal is to create LCZ maps and was created in the framework of the World Urban Database and Access Portal Tools (WUDAPT) project (Demuzere et al., 2021).

3.2 NDVI

Accelerated urbanization results in loss of urban green areas and biodiversity within cities (Haaland and van den Bosch, 2015). How important greenery is to a city's urban microclimate can be concluded based on Figure 12, where it is shown how greenery affects the temperature, i.e. it is visible that the temperature is higher in areas with less greenery, and the temperature is lower in areas with more greenery.

The minimum percentage value of green areas in the European Union is 20%. Some well-planned cities have a significantly larger percentage of green areas (e.g. Vienna with 53%), so such spaces are easier to adapt to climate changes and thermal extremes, which are increasing (Haaland and van den Bosch, 2015). Climatologists also assure us that the situation will be even worse in the future.

Normalized Difference Vegetation Index (NDVI) is used to quantify vegetation greenness and is useful in understanding vegetation density and assessing changes in plant health. The standard NDVI formula (Rouse et al., 1974) used to calculate it is

$$NDVI = (NIR - red) / (NIR + red).$$

The NDVI value ranges from -1 to 1 and shows the health and strength of the crop.

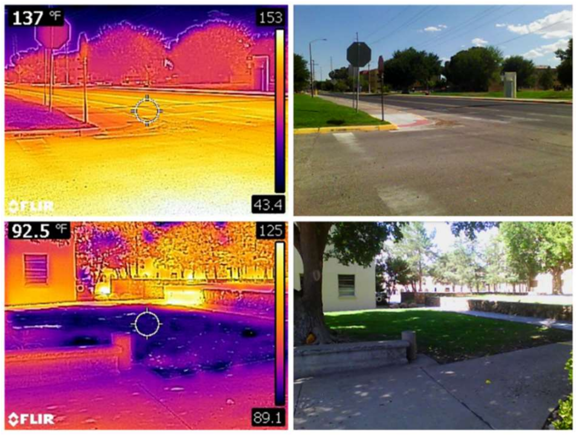

Figure 12 Low albedo, heat-storing materials (up) Lack of Trees and Other Vegetation (down) (according to URL 7)

3.3 The land surface temperature (LST) determination

Today, authors use Landsat thermal data to calculate surface temperature due to good spatial resolution and free data availability. The Landsat satellite is located over the study area every 8 days at 9:42 a.m. (UTC), while the daily maximum surface temperature reaches from 2 p.m. to 6 p.m., which means that it is not the highest daily temperature.

For this research, the most favorable Landsat images were first selected and meteorological data (temperature, humidity, and air pressure) were collected for preprocessing, i.e. calculation of atmospheric correction parameters using the National Centres for Environmental Prediction (NCEP) model (Barsi et al., 2003). With the method, it is possible to convert spatially incoming to spatially outgoing radiance, which is then converted into a temperature using the Planck equation, and neglecting the atmospheric correction can result in systematic errors in predicting the surface temperature of the soil, and the temperature would be 5-10 ºC lower.

The next calculation phase is the conversion of digital numbers into temperatures, that is, the conversion of the digital number into the top-of-atmosphere (TOA) radiance. Landsat OLI and TIRS channel data can be converted to TOA spectral radiance

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using the radiance scaling factor specified in the metadata file (Parham and Fariborz, 2010). After that, the OLI channel data can be converted to the top-of-atmosphere planetary reflectance using the reflectance coefficient found in the metadata file (MTL file).

A more accurate calculation of TOA reflectance requires knowledge of the solar angle for each pixel, which can be replaced with the solar zenith angle of the mid-scene pixel, which can be obtained from the metadata of the Landsat image. The next stage is the conversion of the satellite reflectance temperature, which is done with the help of Planck's equation (Duplančić Leder et al., 2016). TIRS channel data can be converted from spectral radiance (radian) to temperature radiance using a thermal constant from the metadata file. Unsupervised classification was used to display the temperature range, which proved to be more readable for different temperature ranges.

4 RESULTS

4.1 Local Climate Zones (LCZ)

In the study, the LCZ of the wider area of the city of Split was classified in the Google Earth application (Demuzere et al., 2021), and the obtained vector kml classification data. Figure 13 shows the model LCZ for the wider area of Split, estimated according to the Stewart and Oke study (2012).

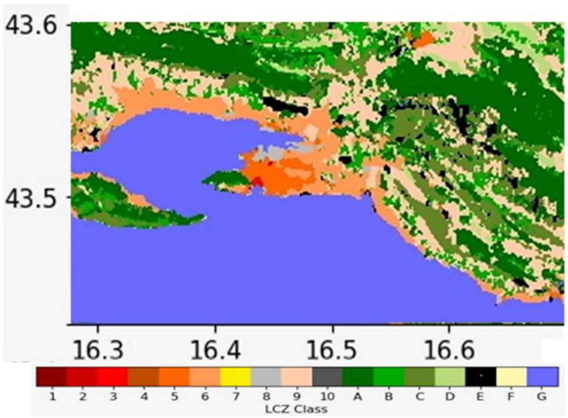

Figure 13. Local climate zone areas of the city of Split.

4.2 Normalized Difference Vegetation Index (NDVI)

NDVI data were obtained by processing Landsat satellite images and showing the condition of the vegetation in the observed area (Figure 14). Large green areas are located on the surface of the Marjan forest park in the west of the peninsula of the city of Split area and in the peri-urban area in the eastern area. Areas covered with vegetation reduce LST and decrease UHI.

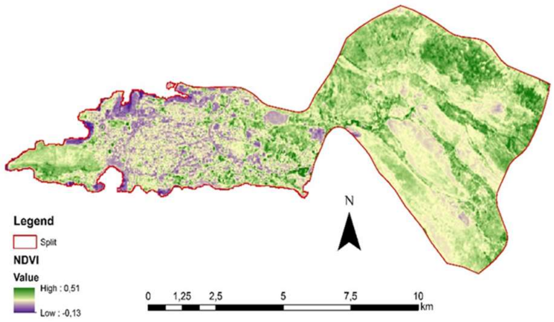

Figure 14. NDVI of the Split City area

4.3 Land Surface Temperature (LST)

Figure 15 shows the LST of the city of Split, the interaction of the LCZ on the LST can be seen. Two significant factors influence the thermal characteristics of the soil, namely the sea area (zone G) and the Marjan forest park area (zone A). The sea heats up more slowly than the land, and due to the difference in temperature in the afternoon, the maestral, a wind that additionally cools the land area, often occurs. This is especially visible on the LST of the coastal area, which is colder than other areas. Likewise, the forest park is a large green area whose temperature is lower than the surrounding area, which also affects the overall temperature of the urban area of the city of Split, which has higher temperatures than the surrounding rural and peri-urban areas.

It is equally visible that the UHI areas are connected to areas of bare soil (zone E; an example of quarries and burnt areas), industrial areas (zone 10; industrial area in the north of the peninsula), and areas of dense construction without greenery (zone 2; an example of the old city core of Split in the city port) (Figure 13 and 15).

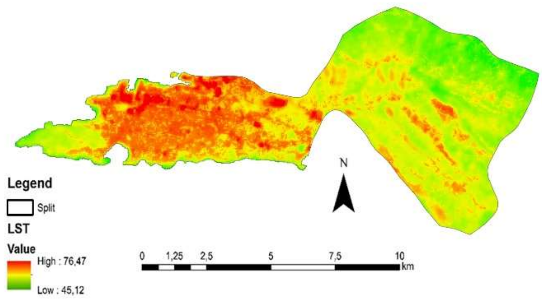

Figure 15. LST of the Split City area

5 DISCUSION AND CONCLUSION

By comparing the LCZ areas of the city of Split with the LST zones determined from Landsat satellite images, we proved the initial assumption that water surfaces and greenery reduce the intensity of UHI. Namely, the coastal areas (except for the northern industrial zones) and the Marjan Forest Park area have significantly lower surface temperatures than other areas. Equally, the highest temperatures, i.e. UHI areas, were observed in the densely built city centre and in the northern part, which is the shipyard, the industrial zone, and the commercial port area.

In the City of Split in the scope of recent urban development interventions, the quantity of vegetation was significantly reduced (especially in the coastal area where the flow of cool sea air – maestral – has been blocked, which may contribute to the formation of UHI.

It can be generally concluded that the application of known research methods of the highest temperatures locations in urban areas (UHI): a) Local Climate Zoning (LCZ); b) Normalized Difference Vegetation Index (NDVI); and c) Land Surface Temperature (LST) on the example of the city of Split, made it possible to identify all critical areas. The proposal to urban planners and people who decide on spatial planning in the city of Split, but also for other coastal cities in the recent era of climate change, is to plan more water and green areas and to avoid dense and tall buildings.

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