Prioritizing the areas for tree planting to help decrease the effect of extreme heat based on Heat Risk Index in the city of Brno

Introduction

Human-induced climate change is particularly evident in urban areas. One of the most important and most extensively studied effects of climate change in urban areas is the increase of air temperature in the city in relation to surrounding areas. This phenomenon is called the urban heat island. Due to the highly transformed surface and the release of heat in municipal and industrial processes, meteorological conditions are subject to numerous modifications. The urban heat island occurs mainly at night, during windless and cloudless weather and it is then that the greatest differences in air temperature between the urban area and its surroundings should occur. Modifications in air and surface temperatures cause significant changes in the living standards of populations around the world. Urban areas are overheating, which is particularly noticeable in the summer (Dubicka et al., 2002; Bokwa et al., 2014).

The urban heat island effect is becoming bigger with increasing urbanization. Currently, the world's urban population continues to increase, including in many regions where the rate of urbanization has slowed compared to previous decades. In 2015, 54% of the world's population (4 billion) lived in urban areas, with this figure estimated to rise to 62% of the world's population (5.4 billion) in 2036. Urban areas are also projected to absorb almost all of the future growth of the world's population (UN-HABITAT Report, 2020).

In response to extreme heat events, cities can incorporate strategic and localized adaptation plans, such as the implementation of green or cool roofs, or increased vegetation and trees to help lower urban temperatures. Initiating this process involves establishing a Heat Risk Index (HRI), which serves as the foundation for a localized adaptation plan for extreme heat. By leveraging the HRI, cities can identify specific areas within the community that warrant prioritized attention in the adaptation plan, facilitating a targeted and effective approach to reducing the urban heat island effect. The choice of input variables will depend on the purpose of the spatial analysis.

1. Case study

The study area covers the city of Brno in the Czech Republic with a total area of 224.18 km2. The purpose of the analysis was to prioritize the areas for tree planting to help decrease the effect of extreme heat. In order to create a heat risk index for the given objective, three input variables were considered: land surface temperature, tree canopy coverage and population density. As the calculated input values used different units of measurement, the standardization was carried out. Subsequently, the standardized values were combined to obtain a Heat Risk Index. The results were presented on the map and analyzed.

1.1. Land cover structure

Land cover type	area in km2	percentage of total area
Bare or sparse vegetation	3,47	1,42
Built-up	51,58	21,12
Cropland	39,82	16,31
Grassland	21,33	8,73
Herbaceous wetland	0,02	0,01
Permanent water bodies	2,45	1,00
Shrubland	0,00	0,00
Tree Cover	105,47	43,19

There are various forms of land use within Brno city. The largest percentage share in the study area belongs to the lands covered by trees (43,19%). Next highest percentage is occupied by built-up areas (21,12%). 16,31% and 8,73% of the area is covered respectively by cropland and grassland. Bare or sparse vegetation occurs only on 1,42% of the study area and 1% of the area belongs to permanent water bodies. Built-up area covers almost the whole historic city center (postcode area: 602 00) and surrounding areas (Figure 1). Moving away from the center, built-up areas are becoming more dispersed. Forests are located mostly in the central and northern part of Brno, while croplands and grasslands can be found mainly in the south. Two main rivers - Svitava and Svratka flow through Brno. One of them - Svratka is going through the biggest water body in the city - The Brno Dam.

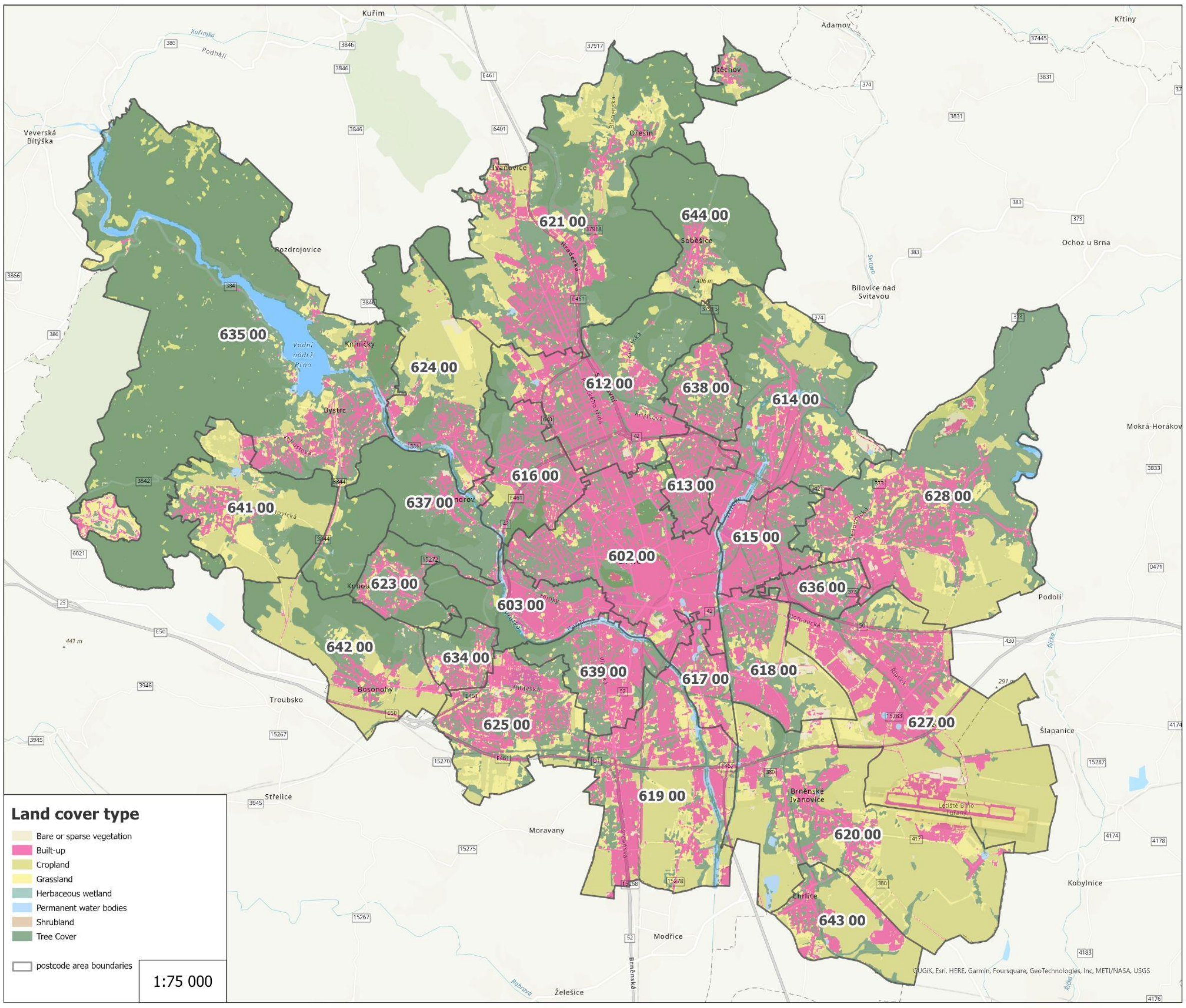


Figure 1. Land cover structure of Brno based on *The European Space Agency WorldCover 2020 Land Cover*

1.2. Average land surface temperature

Average land surface temperature distribution in the city of Brno strongly overlaps with the land cover. Built-up areas are having higher temperature values and it impacts as well the croplands and grasslands that are surrounding the built-up areas (Figure 2). The lowest average land surface temperatures occur on the land covered by trees without a high density of built-up areas, especially in the northern part of the city and the northern-east part, where the Brno's Dam is located.

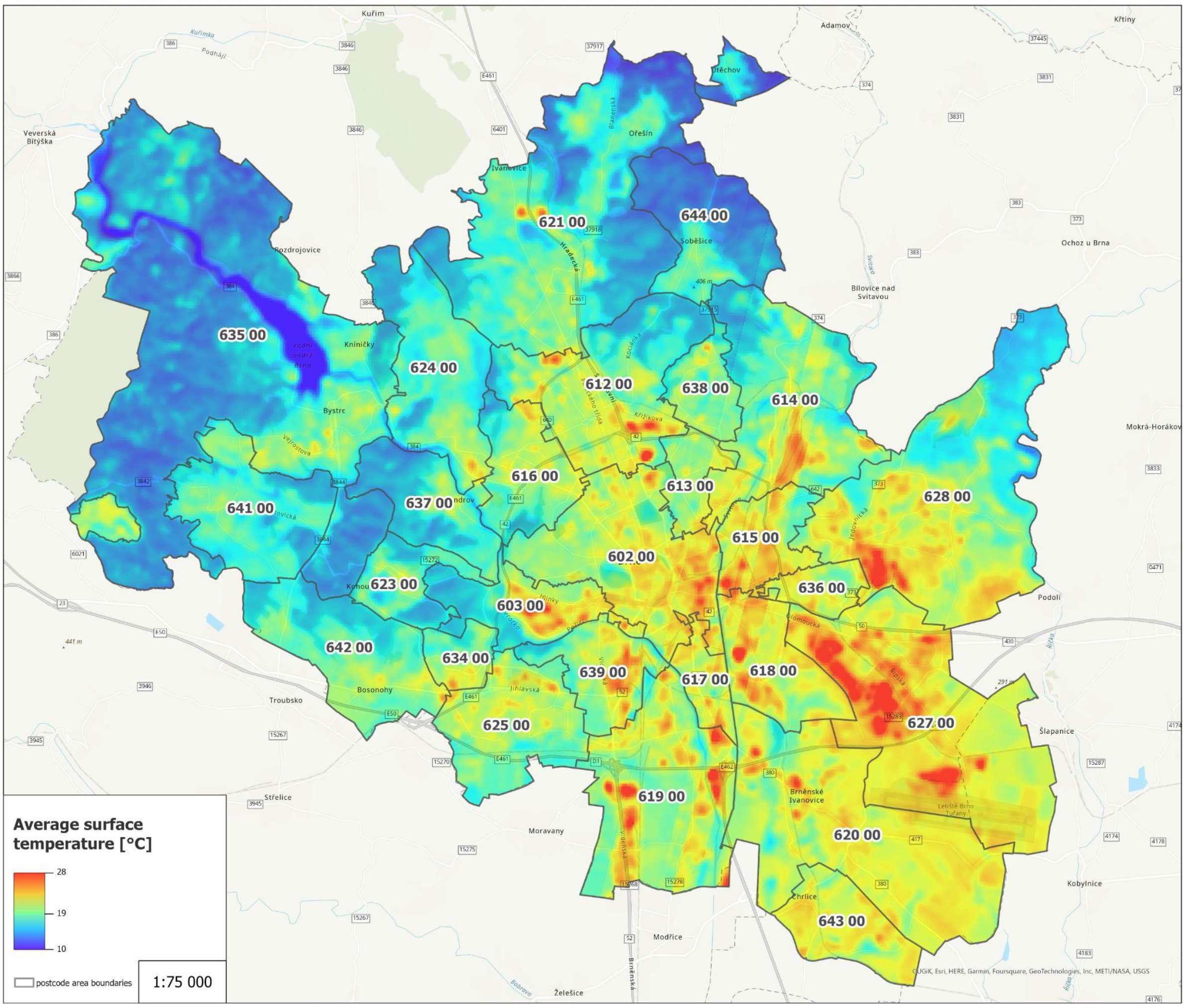


Figure 2. Distribution of average land surface temperature [°C]

1.3. Population density

The highest value of population density were observed in the central part of the city, mainly in the following postcode areas: **613 00** (8099 population/km^2), **634 00** (6758 population/km^2), **602 00** (6307 population/km^2) and **638 00** (6242 population/km^2). High values, from range 4000 - 5000 population/km^2 were noted in zone **616 00** (4517 population/km^2), **623 00** (4463 population/km^2), **625 00** (4334 population/km^2), **615 00** (4026 population/km^2) and **636 00** (4908 population/km^2). When analyzing the map, it is visible that population density values were decreasing with moving away to the borders of Brno. The lowest values of population density were observed in the southern part of the city in the following postcode areas: **641 00** (451 population/km^2), **644 00** (413 population/km^2), **620 00** (366 population/km^2), **642 00** (340 population/km^2) and **619 00** (327 population/km^2).

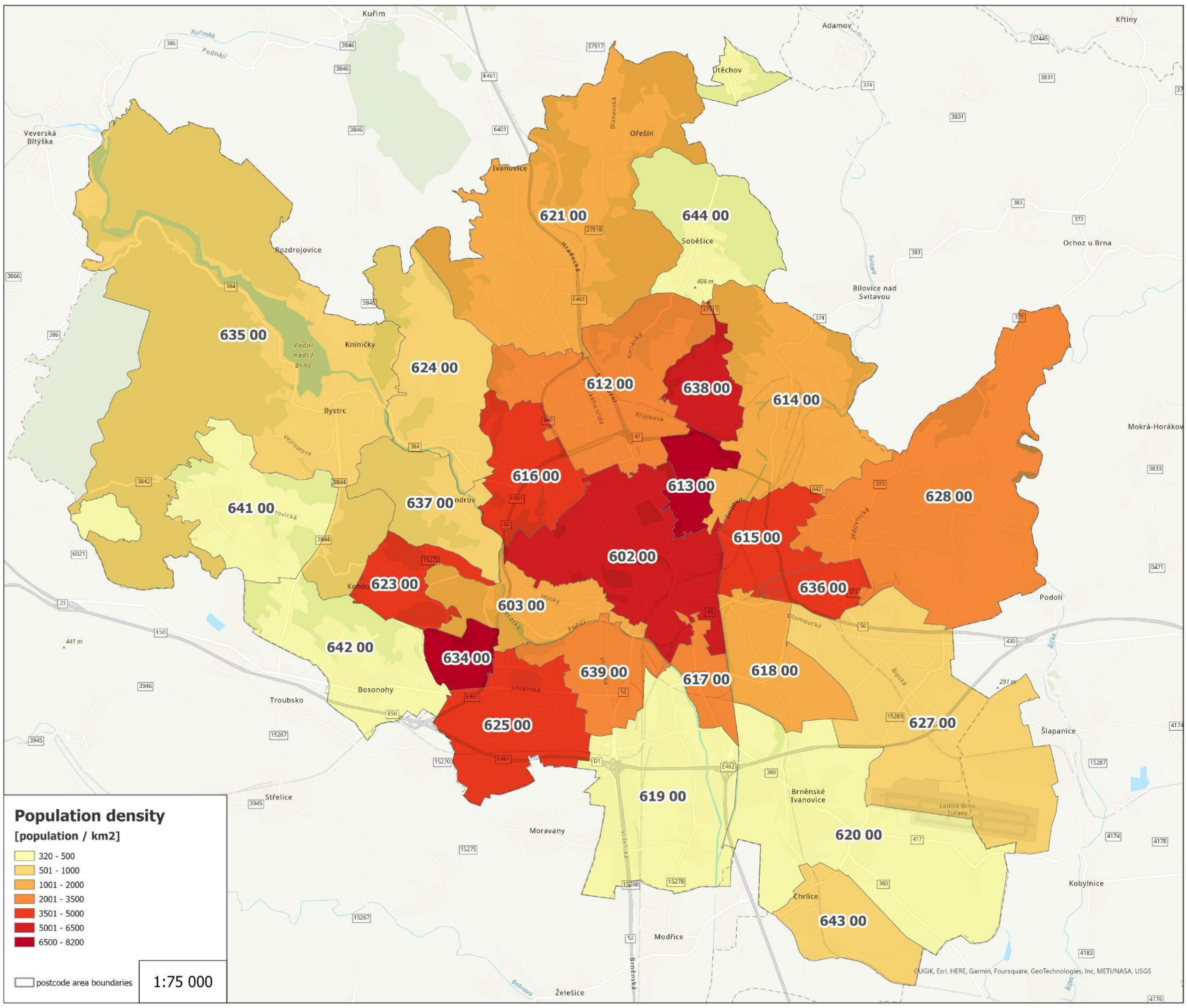


Figure 3. Population density within each postcode area in the city of Brno [population/km^2]

2. Data

All data used in this study were retrieved from ArcGIS Living Atlas provided by Esri, which holds a collection of ready-to-use global geographic content, such as imagery, basemaps, boundaries, demographics, earth observations, urban systems and historical maps. Boundaries of the city with a total population count were extracted from ‘’*Czech Republic Postcodes5 Boundaries”* layer. Land surface temperature was derived from the ‘’*Multispectral Landsat”* imagery layer by extracting one of the two multispectral bands from Thermal Infrared Sensor (TIRS) held by Landsat 8 and Landsat 9 imagery. Tree canopy coverage was calculated using ‘’*The European Space Agency WorldCover 2020 Land Cover”* layer. This map contains 11 different land cover classes at 10 m resolution including ‘’*Tree Cover”* class, which contains any geographic area dominated by trees with a cover of 10% or more: areas planted with trees for afforestation purposed and plantations as well as tree covered areas seasonally or permanently flooded with fresh water except for mangrove.

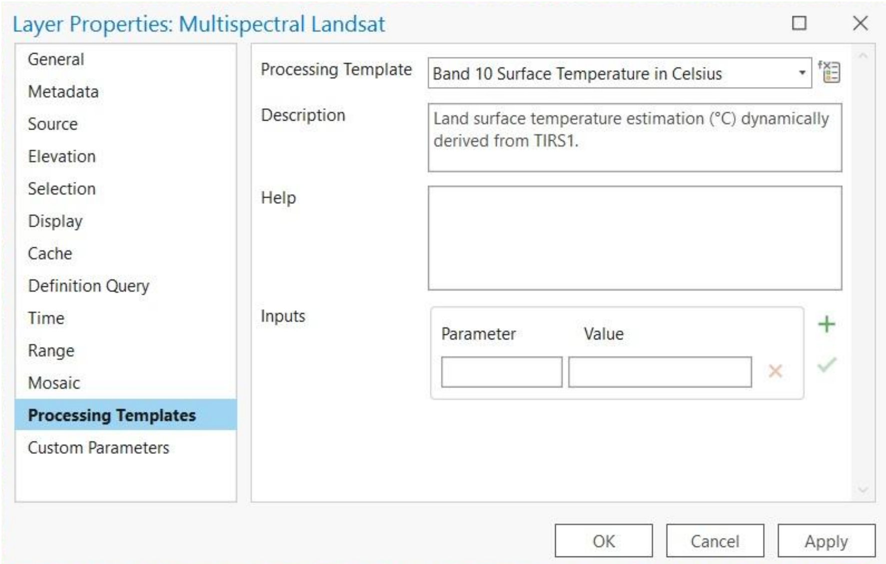
3. Tools and methods

3.1.1. Landsat data conversion and transformation procedure

In order to derive proper land surface temperature visualization, the following procedures were applied: configure processing template, mosaic operator and definition query in the layer properties.

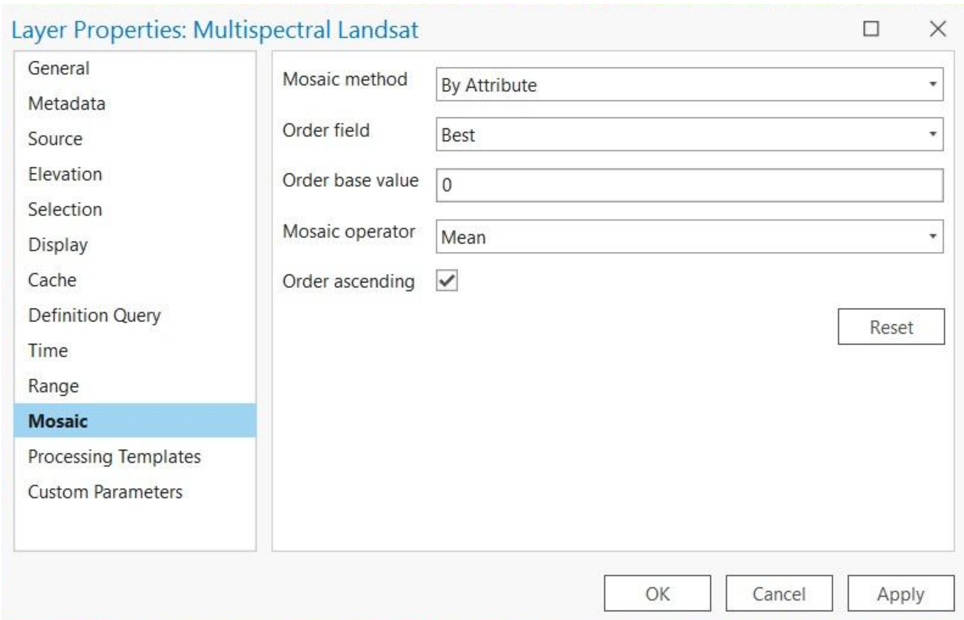
3.1.2. Processing Template

In the *Processing Template* tab that is accessible via the *Properties* option of the *Multispectral Landsat* imagery layer, *Band 10 Surface Temperature In Celsius* was selected as the processing template. This template identifies land surface temperature in degrees Celsius.



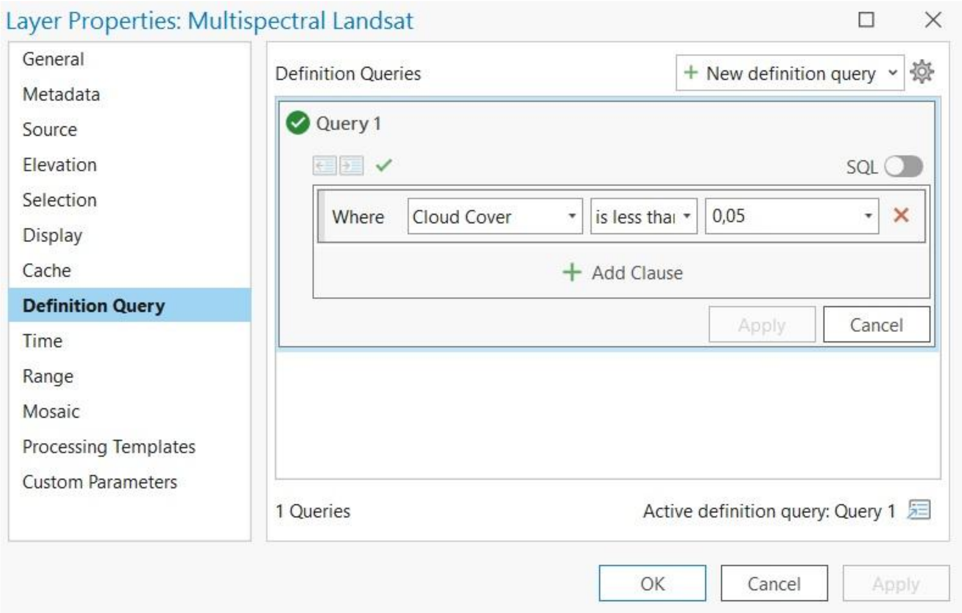
3.1.3. Mosaic Operator

The imagery layers may include overlapping cells. The mosaic operator tool enables defining how these overlapping cells should be resolved. For the purpose of the analysis the mosaic operator tool was set to Mean, which provided the average land surface temperature for overlapping cells.



3.1.4. Definition Query

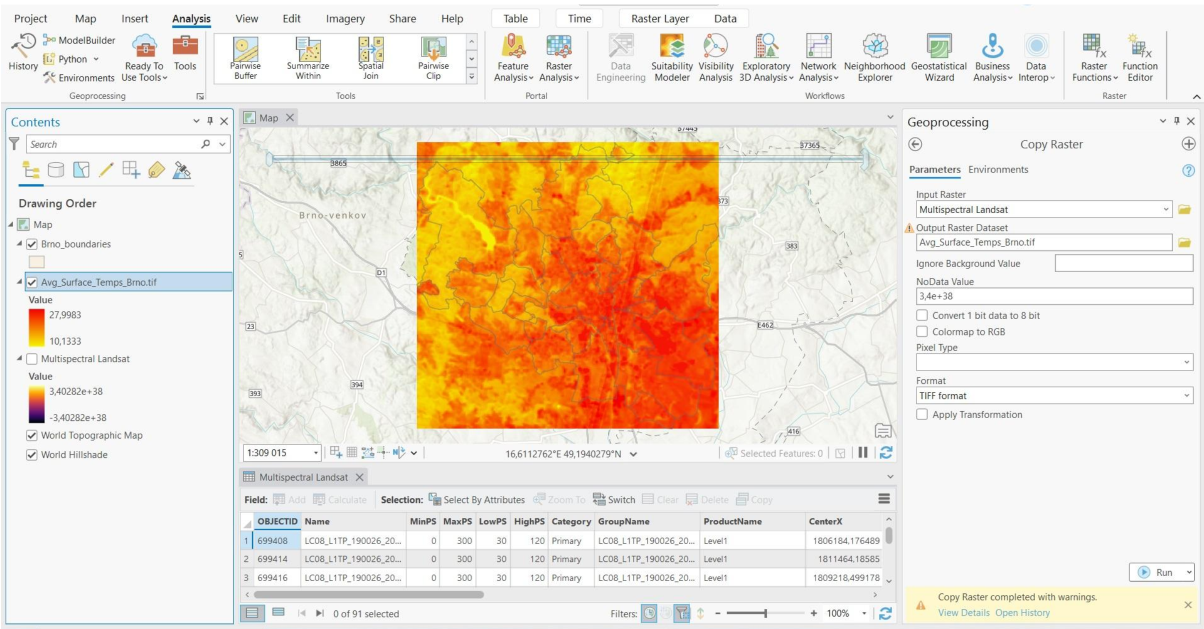
The Multispectral Landsat imagery contains clouds and cloud shadows, which could interfere with the analysis. In order to decrease analysis interference that could be caused by cloudy images, a definition query was used to filter out all images with more than 5-percent cloud cover.



3.1.5. Defining study area for the land surface temperature

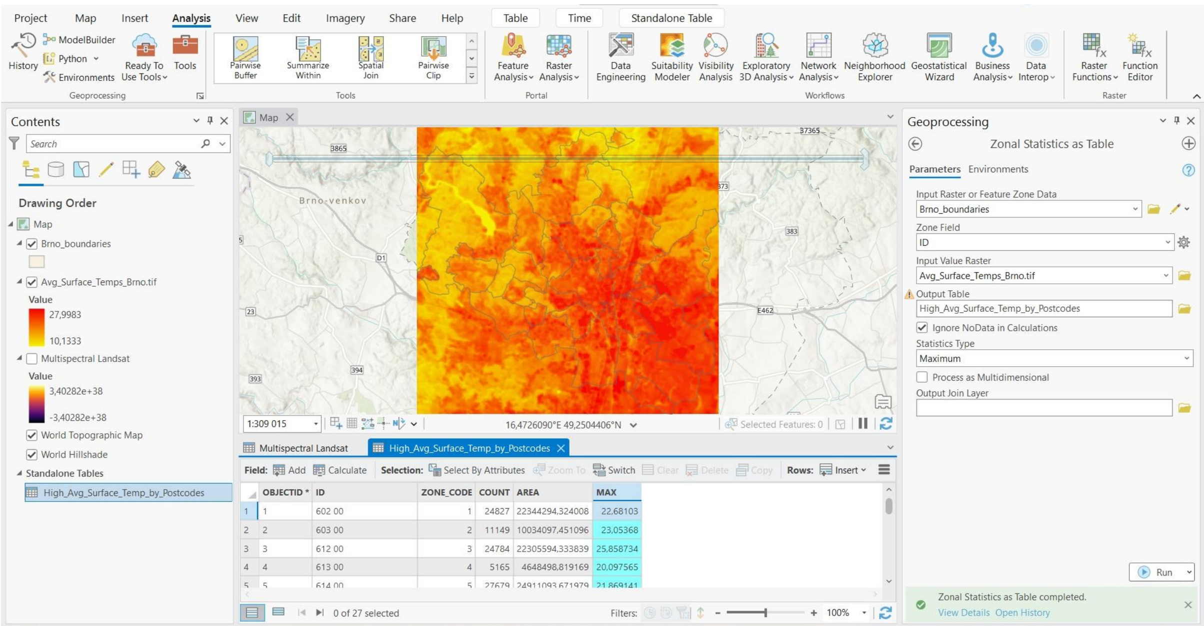
Due to the *Multispectral Landsat* imagery layer covers the whole globe, the extent of the land surface temperature layer had to be configured to match boundaries of the Brno city. The following steps were done for that purpose:

→ Zooming to the layer with Brno boundaries
→ Opening the *Multispectral Landsat* imagery layer attribute table and select *Filter by Extend* button to show records for the current map extent only
→ Opening *Copy Raster* tool, go to *Environments* tab and select Brno boundaries layer in *Extend by Layer* option
→ Inserting input and output raster data in *Parameters* tab and running the tool



3.1.6. Summarizing temperature values in a table

The final step of deriving the land surface temperature was to summarize all the temperature values in each postcode polygon in Brno to determine the maximum average temperature value in degrees Celsius. *Zonal Statistics as Table* tool was used for this calculation.

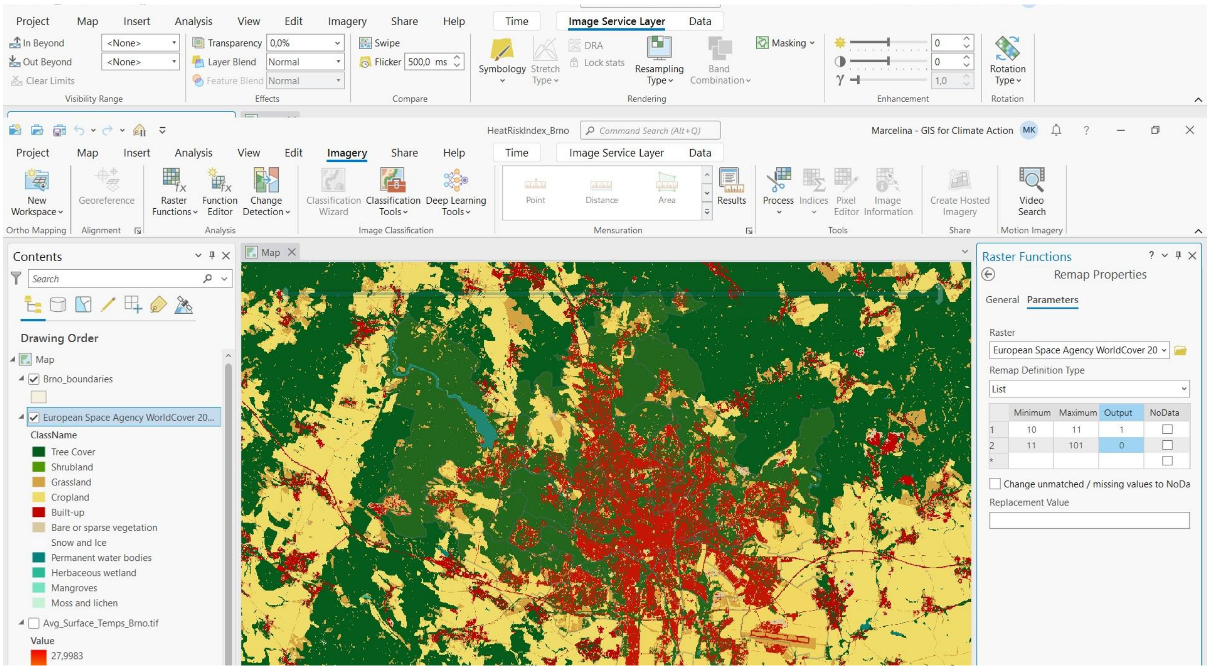


3.2. Tree canopy coverage identification

In order to derive tree canopy coverage from the *The European Space Agency WorldCover 2020 Land Cover* layer, Tree cover class was isolated and the amount of coverage for each Brno postcode polygon area was calculated.

3.2.1. Isolating areas covered by trees

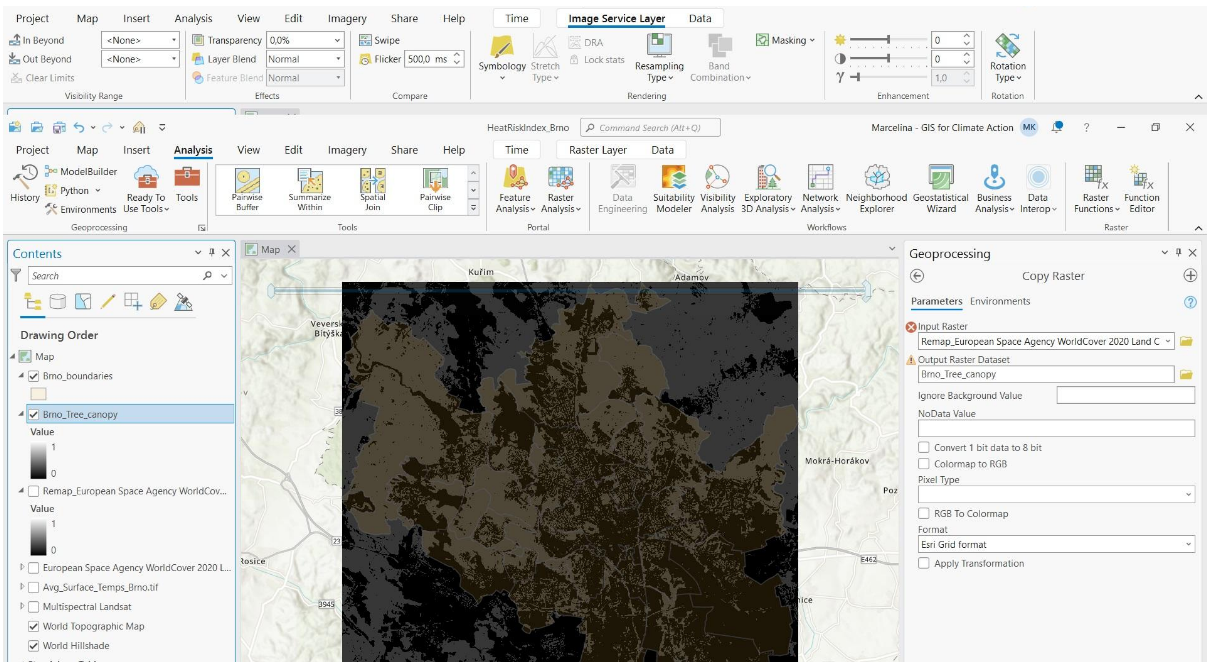
The cells that contain land covered by trees were isolated using the *Remap raster* function that allows to group cell values and then assign new values to these groups. As it is described on the item page of the land cover layer, tree cover cells have a value of 10. In addition to this, the values were remapped to put a value of 1 for tree cover cells and 0 for the remaining cells.



3.2.2. Defining study area for the tree coverage data

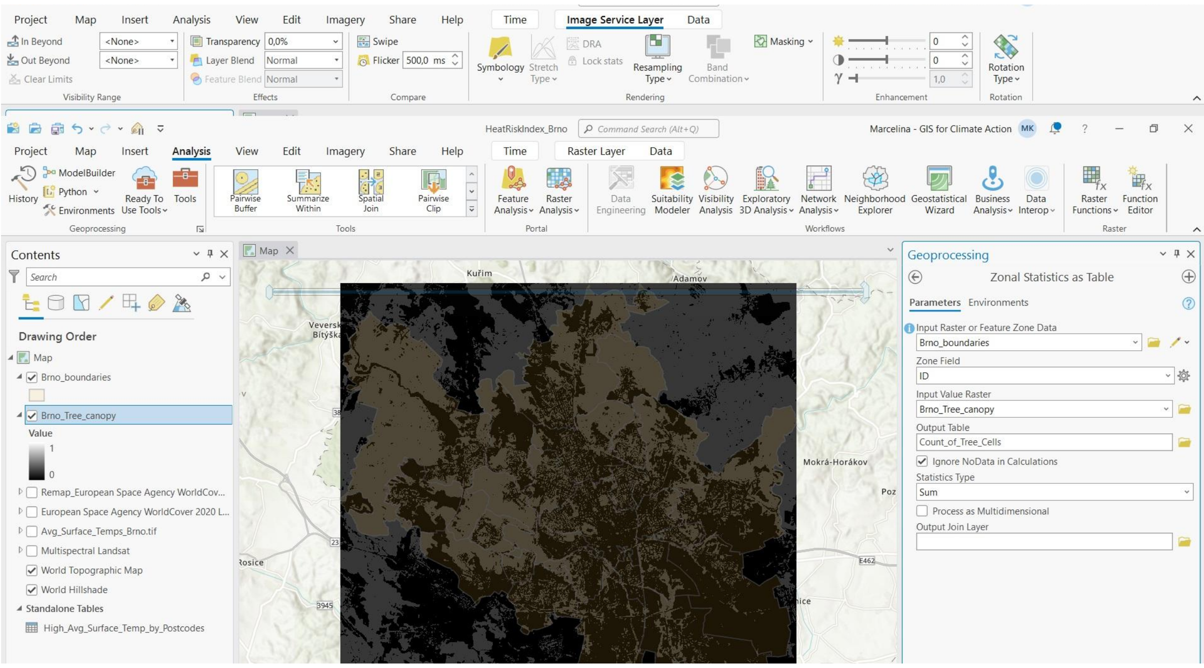
Due to the *European Space Agency WorldCover 2020 Land Cover* layer covers the whole globe, the extent of the land surface temperature layer was configured to match boundaries of the Brno city. The same approach as for the land surface temperature layer were used:

→ Zooming to the layer with Brno boundaries
→ Opening the *European Space Agency WorldCover 2020 Land Cover* layer attribute table and select *Filter by Extend* button to show records for the current map extent only
→ Opening Copy Raster tool, go to *Environments* tab and select Brno boundaries layer in *Extend by Layer* option
→ Inserting input and output raster data in *Parameters* tab and running the tool

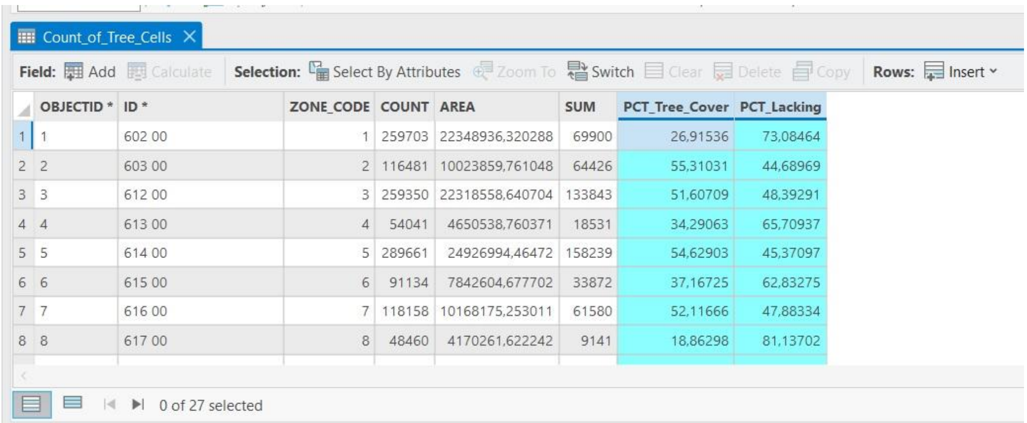


3.2.3. Calculating tree canopy coverage

Tree canopy coverage as a Heat Risk Index input variable is presented as two percentages for the area of study: percent tree cover and percent lacking tree cover. First step to calculate the required percentage values was to create a table that identifies the total number of tree cover cells in each Brno postcode polygon using the *Zonal Statistics As Table* tool with the *Statistics* Type parameter set to *Sum*.



Next step was to calculate the percentage of tree canopy cover in the *Calculate Field* tool available in the attribute table using *Count* and *Sum* fields. The formula for this calculation was the sum of the tree canopy cover cells divided by the total count of cells, multiplied by 100. Then, the percent lacking tree canopy coverage for each Brno postcode polygon was calculated using the following formula: ''100 - percentage of tree canopy cover.''



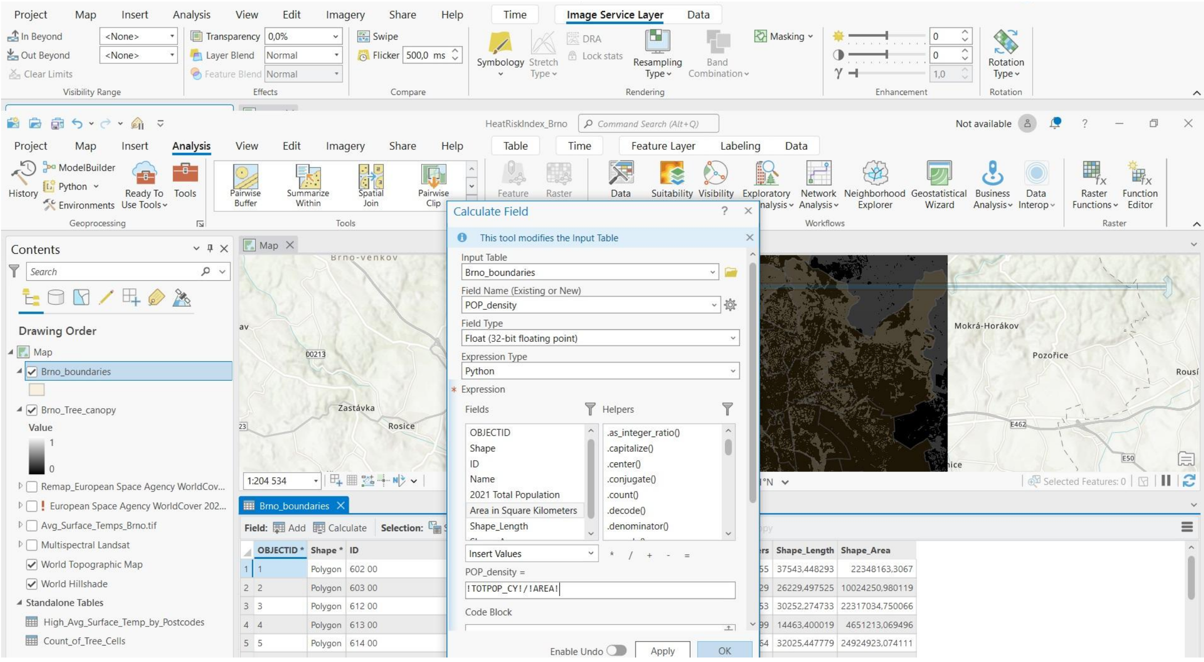
Count_of_Tree_Cells

	OBJECTID *	ID *	ZONE_CODE	COUNT	AREA	SUM	PCT_Tree_Cover	PCT_Lacking
1	1	602 00	1	259703	22348936,320288	69900	26,91536	73,08464
2	2	603 00	2	116481	10023859,761048	64426	55,31031	44,68969
3	3	612 00	3	259350	22318558,640704	133843	51,60709	48,39291
4	4	613 00	4	54041	4650538,760371	18531	34,29063	65,70937
5	5	614 00	5	289661	24926994,46472	158239	54,62903	45,37097
6	6	615 00	6	91134	7842604,677702	33872	37,16725	62,83275
7	7	616 00	7	118158	10168175,253011	61580	52,11666	47,88334
8	8	617 00	8	48460	4170261,622242	9141	18,86298	81,13702

0 of 27 selected

3.3. Population density calculation

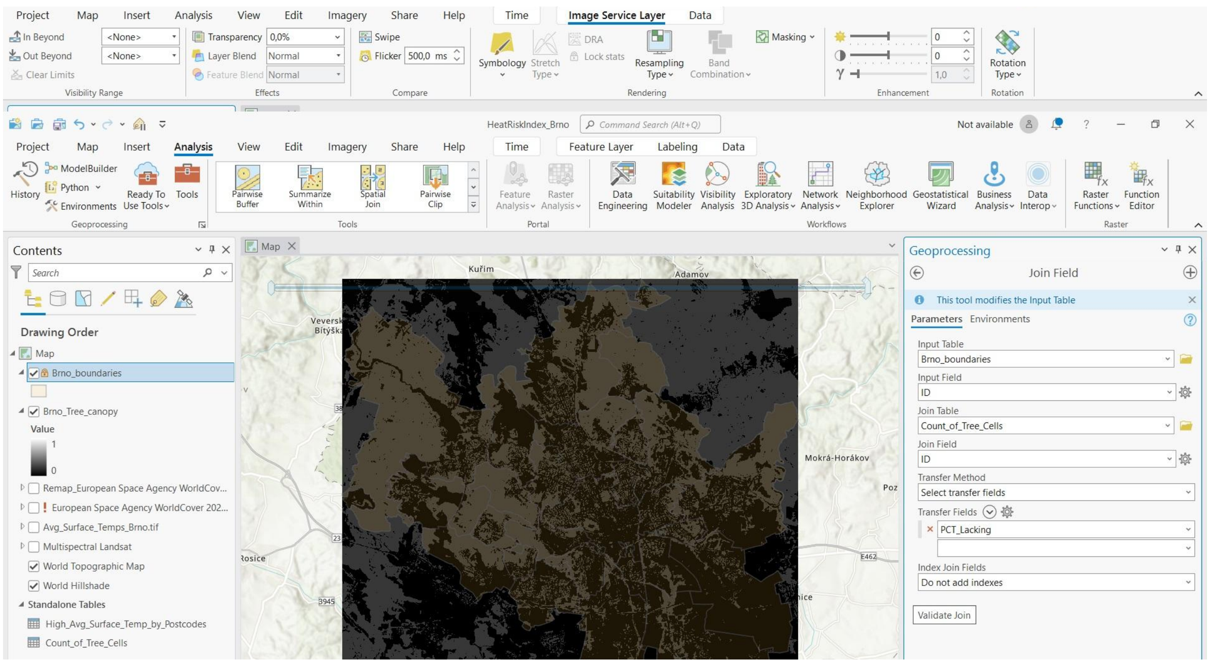
The third input variable needed to create Heat Risk Index (population density), was calculated using the *Calculate Field* option available in attribute table of Brno boundaries layer by dividing total population of each postcode polygon by its area.



3.4. Combining the input variables to create Heat Risk Index (HRI)

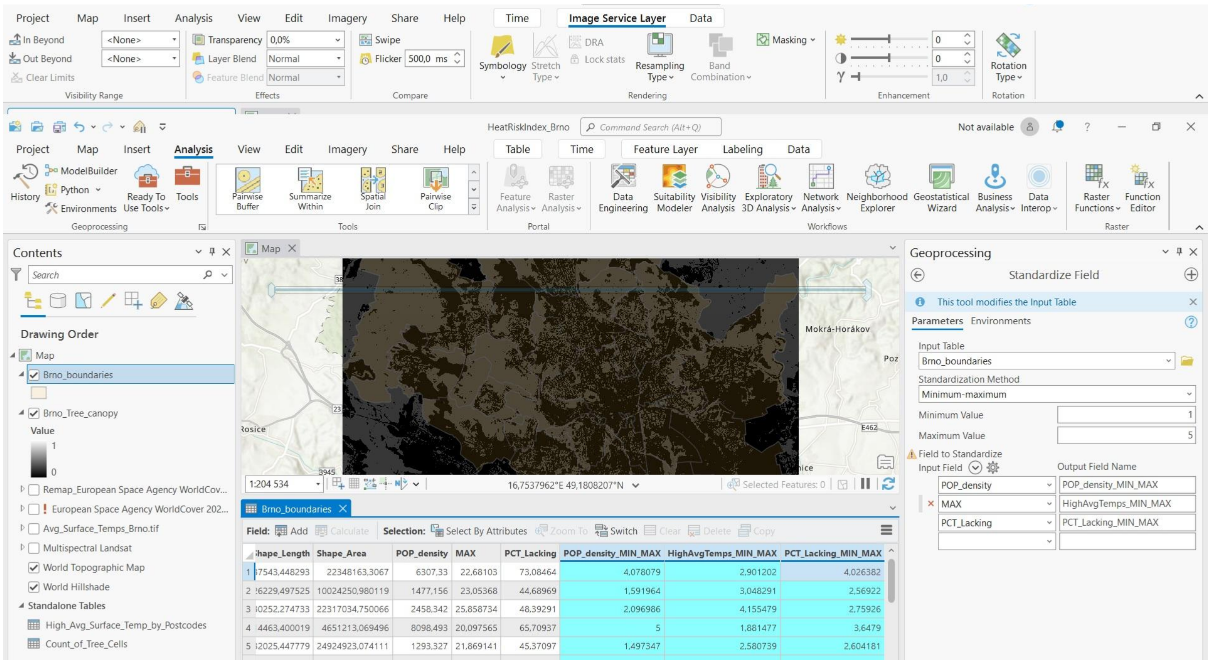
3.4.1. Joining tables

After the input variables have been prepared, they were combined to create HRI. Due to the data were being stored in three separate tables, *Join Field* tool was used in order to put calculated input variables into one table.



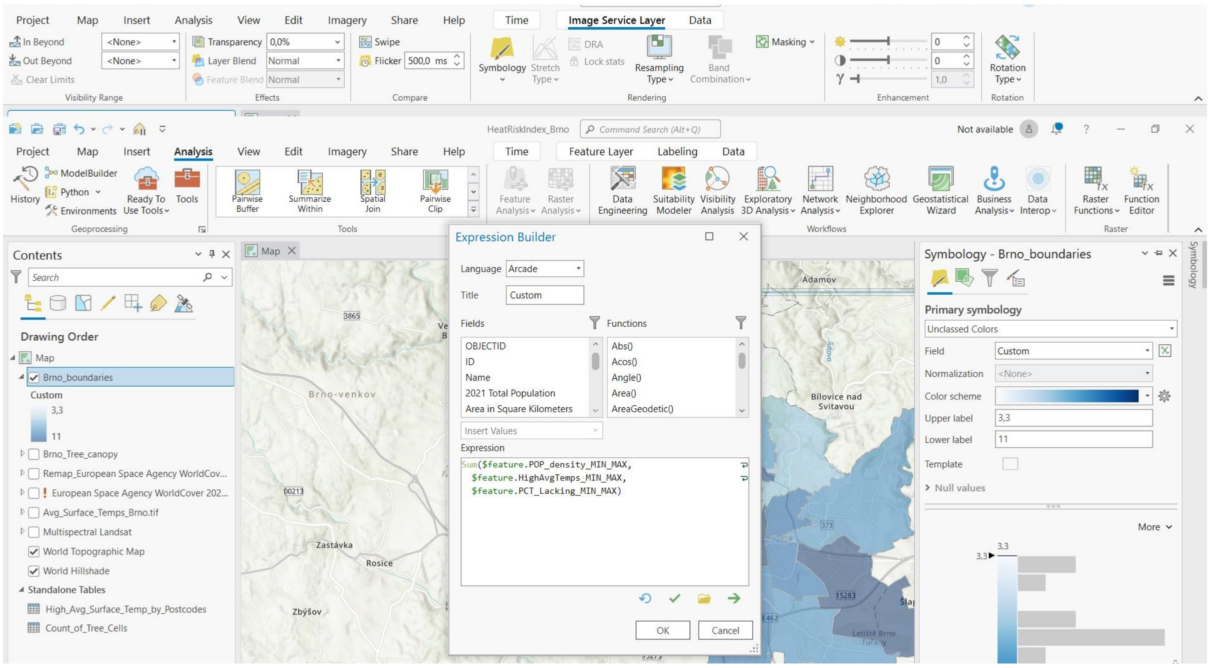
3.4.2. Standardizing data

For this purpose the *Standardize Field* tool was used with *minimum-maximum* standardization method using 5-point scale, where 1 represents area with the lowest heat risk index and 5 represents the areas with the highest heat risk index.



3.4.3. Visualizing the Heat Risk Index on the map

In order to visualize Heat Risk Index, *Arcade expression* was used to summarize the standardized input variables. This expression was added when going to the *Symbology* pane of Brno boundaries layer and selecting *Unclassed Colors* as *Primary Symbology* and then *Set An Expression* button. Sum function was chosen and standardized input variables were added.



4. Results

4.1. Heat Risk Index (HRI) distribution

In the Heat Risk Index distribution within the borders of Brno city some patterns can be observed. Mainly, areas north and west of the central part had a lower value of Heat Risk Index, while in the central part and on south and east areas of the center higher values of the index occurred. The value above 10,0 of the HRI was noted in three postcode areas: **627 00** (11,13 HRI), **602 00** (11,01 HRI) and **613 00** (10,53 HRI).

The HRI values from the range 9,0 - 10,0 were observed in the following areas: **615 00** (9,90 HRI), **618 00** (9,71 HRI), **619 00** (9,60 HRI), **617 00** (9,34 HRI), **634 00** and **625 00** (9,25 HRI), **612 00** (9,01 HRI).

Slightly lower HRI values from range 7,0 - 9,0 were noticed in the following areas: **620 00** (8,79 HRI), **628 00** (8,68 HRI), **638 00** (8,58 HRI), **639 00** (8,50 HRI), **636 00** (8,44 HRI), **643 00** (8,05 HRI), **616 00** (7,88 HRI), **603 00** (7,21 HRI).

The postcode areas that had the low values of HRI, compared to the mentioned above are as the follows: **624 00** (6,88 HRI), **614 00** (6,68 HRI), **623 00** (6,64 HRI), **621 00** (6,45 HRI), **642 00** (6,36 HRI) and **641 00** (6,18 HRI). The lowest HRI values belonged to **635 00** postcode area (4,14 HRI), **637 00** (3,94 HRI) and **644 00** (3,31 HRI).

						standardized values			
postcode area	total population 2021	area [km2]	population density [per km2]	maximum average temperature [°C]	percent lacking tree cover	population density [per km2]	maximum average temperature [°C]	percent lacking tree cover	HDI (Heat Risk Index)
627-00	9271	15,9	583,08	28,0	92,06	1,13	5,00	5,00	11,13
602-00	60235	9,55	6307,33	22,7	73,08	4,08	2,90	4,03	11,01
613-00	16116	1,99	8098,49	20,1	65,71	5,00	1,88	3,65	10,53
615-00	13487	3,35	4025,97	24,2	62,83	2,90	3,50	3,50	9,90
618-00	8176	4,6	1777,39	25,4	72,21	1,75	3,99	3,98	9,71
619-00	3506	10,72	327,05	25,6	82,80	1,00	4,07	4,52	9,60
617-00	5515	1,78	3098,32	21,6	81,14	2,43	2,47	4,44	9,34
625-00	27302	6,3	4333,65	21,2	69,61	3,06	2,34	3,85	9,25
634-00	11218	1,66	6757,83	21,1	46,35	4,31	2,29	2,65	9,25
612-00	23428	9,53	2458,34	25,9	48,39	2,10	4,16	2,76	9,01
620-00	5610	15,34	365,71	23,1	86,26	1,02	3,07	4,70	8,79
628-00	39460	17,62	2239,50	24,8	52,49	1,98	3,73	2,97	8,68
638-00	15479	2,48	6241,53	20,4	43,96	4,04	2,01	2,53	8,59
639-00	8927	3,74	2386,90	23,6	56,75	2,06	3,25	3,19	8,50
636-00	7951	1,62	4908,03	20,8	51,33	3,36	2,17	2,91	8,44
643-00	3675	4,03	911,91	21,1	81,76	1,30	2,28	4,47	8,05
616-00	19602	4,34	4516,59	20,4	47,88	3,16	1,99	2,73	7,88
603-00	6337	4,29	1477,16	23,1	44,69	1,59	3,05	2,57	7,21
624-00	7278	7,55	963,97	20,7	61,17	1,33	2,13	3,41	6,88
614-00	13761	10,64	1293,33	21,9	45,37	1,50	2,58	2,60	6,68
623-00	12451	2,79	4462,72	19,6	30,27	3,13	1,69	1,83	6,64
621-00	24461	20,03	1221,22	22,0	40,14	1,46	2,65	2,34	6,45
642-00	2429	7,15	339,72	21,0	55,16	1,01	2,25	3,11	6,36
641-00	3565	7,9	451,27	19,1	65,46	1,06	1,48	3,64	6,18
635-00	24924	37,53	664,11	19,7	18,63	1,17	1,73	1,23	4,14
637-00	4092	4,51	907,32	19,5	14,11	1,30	1,64	1,00	3,94
644-00	2993	7,24	413,40	17,9	19,34	1,04	1,00	1,27	3,31

Table 1. Input variables and HRI calculated per each postcode area

4.2. Prioritizing the areas for tree planting

Looking at the map with the distribution of HRI in the city of Brno (Figure 4), it can be easily determined that the area of interest to prioritize tree planting should include the central, eastern and southern part of Brno. Based on the analysis of the index distribution, the first postcode area that should be determined as the highest need of planting the trees in order to cool the city, is **627 00** as the highest HRI value was observed within this area. The reason can be probably found in the land cover structure containing mainly cropland, built-up areas and grassland. Built-up areas, especially with continuous urban fabric, mostly made of concrete and asphalt, have a higher heat storage capacity than forest or water areas. Moreover, the heat stored in such areas is released more slowly. Similarly, croplands due to the lack of high vegetation, are exposed to direct sunlight on the ground. Vegetation also releases moisture through a process called transpiration, which has a cooling effect.

However, **627 00** postcode area contains international airport and due to the airport zoning regulations, trees are not planted within some distance for safety reasons. Therefore, trees could be planted in the southern part of this area in order to cool the inhabited zones. Nonetheless it must be taken into account that urbanization and the development of nearby areas can lead to higher temperatures in the surrounding areas, so it is more likely for the north part of the **627 00** postcode zone to be constantly affected by the southern part. Regarding this, other solutions than planting trees could be discussed in order to cool the airport area.

The next two areas with the highest value of HRI: **613 00** and **602 00** are covered in majority by the built-up areas and having first (613 00) and the third (602 00) highest value of population density. Continuous urban fabric made of concrete and asphalt make the areas absorb huge amounts of sunlight. Although about 30% of the mentioned zones are covered with the trees, the neighbor postcode zones with high density of built-up areas make an impact on the land surface temperature in the considered zones. Therefore, when taking into account, not only cooling the city, but as well improving inhabitants comfort, both areas should be prioritized in the adaptation plan.

The next group to be considered contains the areas with the HRI range from 9,00 to 10,00 (**612 00**, **615 00**, **617 00**, **618 00**, **619 00**, **625 00**, **634 00**). There are the areas that are adjacent to the zones mentioned above with the highest value of HRI. In most of the areas listed above, the continuous urban fabric covers the largest amount of the surface (**615 00** - 56%; **617 00** - 55%; **619 00** - 37%; **625 00** - 34%; **618 00** - 22%). Only two postcode areas are covered with the higher percentage with the trees than built-up areas: **634 00** (tree cover: 54%, built-up: 30%) and **612 00** (tree cover: 52%, built-up: 37%). However, postcode area **612 00** are characterized by the highest maximum average surface temperature in this group, while **634 00** postcode area is having the highest value of population density within the considered group. Therefore, the areas with the higher percent lacking tree coverage value in this group could be prioritized to help cooling the city (**615 00**, **617 00**, **619 00**, **625 00**, **618 00**) as well as the zone with the highest maximum average surface temperature - **612 00**.

Further zones to prioritize could be considered when making an adaptation plan for the city of Brno. Planting trees in the areas proposed above would decrease the heat risk index not only within these zones, but also it could have a positive impact on the surrounding areas. After adapting the changes to the areas pointed out in the analysis above, calculation of Heat Risk Index could be conducted with new data to check the results and identify new potential areas for such activities. Moreover, more input variables could be added in order to adjust the analysis for another purpose e.g. extend the analysis with age and income data to identify areas with vulnerable populations.

The above analysis serves as an illustrative example showcasing the utility of the Heat Risk Index and highlights the huge capabilities of ArcGIS as a powerful software equipped with extensive datasets and numerous analytical tools. The flexibility of ArcGIS positions it as a valuable resource for cities engaged in adaptation planning, offering a comprehensive suite of features to address complex challenges related to climate resilience.

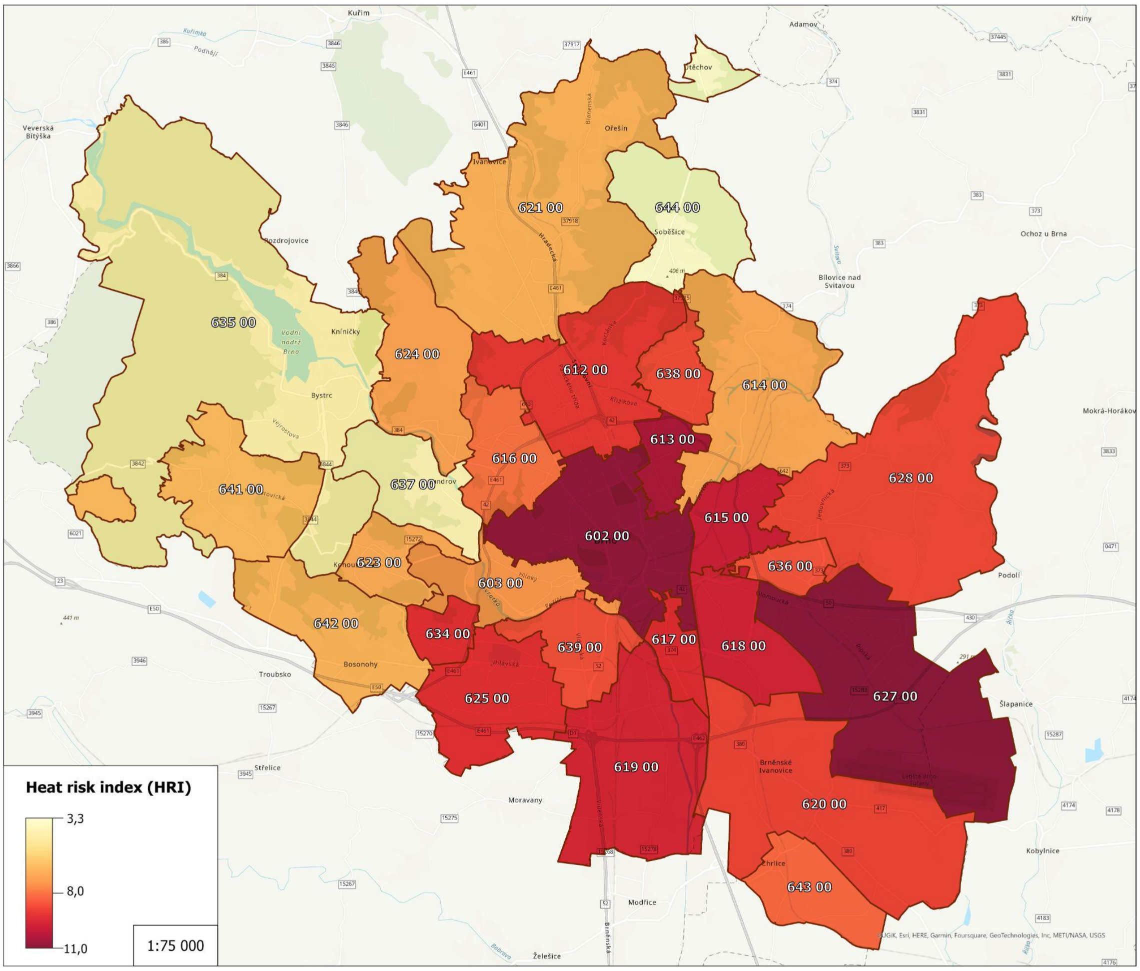


Figure 4. Heat Risk Index (HRI) per each postcode area in the city of Brno

1) **Dubicka M., Dubicki A., Szymanowski M.,** 2002, Klimat Wrocławia. W: Środowisko Wrocławia–Informator
2) **UN-HABITAT Report,** World Cities Report 2020, The Value of Sustainable Urbanization