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Delimitation and Prioritization of Climate-Affected Areas Using the Example of a Post-Industrial City

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Abstract: This study adapted and tested an approach to identifying areas that are particularly vulnerable to climate-related hazards using the example of the post-industrial city of Knurów in Poland. This study applied a multi-criteria method using the analytical hierarchy process based on GIS map data. The analysis was divided into statistical regions defined for the city. Fifteen attributes were defined for each statistical region. The applied methods provided verified spatial information related to specific climate change hazards. The results showed that the most vulnerable areas were the areas with intensive development in the city center and in the southwestern part of the city. Among the 15 attributes, the most significant were T1 (number of inhabitants in zones with a higher potential thermal risk index by statistical district) with a value of 0.163, G2 (percentage of the sum of tree-shaded areas in built-up areas within the territory of a given statistical district) with 0.143 and H3 (number of buildings in areas of drainless basins and 100-year water). This method effectively identified the most vulnerable areas. The use of such a method can help in the preparation of planning documents and urban adaptation plans by determining the thermally and hydrologically vulnerable areas with the least developed green infrastructure as an exposure-mitigating factor.

Keywords: urban climate; urban greenery; exposure to hydrological events; exposure to elevated temperatures; vulnerable areas; urban planning; multi-criteria analysis; analytical hierarchy process; GIS

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1. Introduction

Progressive climate change contributes to the need to delineate areas of cities that are vulnerable to different hazards, so that urban planners and local governments can prioritize and target local climate change adaptation measures in cities.

For effective adaptation measures in urban areas, it is necessary to define hazards, urban challenges and problems for sensitive and vulnerable areas [1]. This approach enables an appropriate selection of adaptation measures and consequently better adaptation to climate change, thus improving the safety of residents and infrastructure. Thorough recognition of the city's situation provides the opportunity to determine its development potential and weaknesses. This is a prerequisite (starting point) for the creation of a climate change adaptation plan as a strategic tool for the management of the city. In particular, the delineation of vulnerable areas is important for spatial planning, which is one of the most important policy instruments for climate change adaptation [2]. It is also important for the prioritization of measures to be taken by the city administration as part of the climate change adaptation policy [3].

The assessment of climate change hazards is a complex task and depends on the specific objective and context of the assessment, including the geographical, structural, environmental and socio-economic conditions of the past, current and planned development of the city. Depending on these, the available methods are appropriately selected between and the selections are applied [4]. To date, a variety of potential impacts (and potential benefits) of climate change on cities have been identified. These include (1) impacts on sea level rise in coastal areas (related to storms), (2) impacts of extreme events on built infrastructure, (3) impacts on health, (4) impacts on water resources and (5) impacts on energy availability [4]. A better understanding of the interaction between climate and land surface in the past and present is very important, especially for predicting its future changes. In order to effectively address changing development needs and priorities, it is necessary to gain an understanding of climate variability by using novel tools, such as the nowcasting tool, which provides an estimation of the average waiting time for extreme values of climate parameters [5]. For coastal cities, there is the modeling of tropical cyclones (IMT) using cluster algorithms that evaluate the instability of the atmosphere–ocean system [6,7]. The new tools make it possible to better understand the interplay between climate impacts, mitigation strategies, adaptation measures and sustainable progress [5].

There are different methods for selecting the most vulnerable areas in the city. Researchers are investigating the use of participatory mapping and various machine learning algorithms and developing new methods based on artificial neural networks (ANNs) [8–10]. The use of these new methods makes it possible to supplement and confirm the results obtained with other methods, e.g., as part of a multi-criteria analysis with GIS models [10].

Multi-criteria analysis (MCA) is a method also known as multiple-criteria decision-making (MCDM) or multiple-criteria decision analysis (MCDA) [11]. It is a method in which different techniques and tools can be used to evaluate data with respect to multiple criteria and attributes [11]. One of the most commonly used techniques in MCA is the analytic hierarchy process (AHP), which is based on linear algebra and allows ratio scales to be obtained from paired data comparisons [12,13].

In the context of designating areas sensitive to climate change, these statistical methods often rely on georeferenced databases and maps. GIS-based tools enable robust spatial analysis and modeling of vulnerability at the urban scale [14]. A geographic information system (GIS) integrated with MCA forms a multi-criteria spatial decision support system (MC-SDSS) [15].

Sustainable urban development has become an important goal of European societies, and the phenomena of climate change in cities are recognized as major problems. There are many hazards related to the urban population and infrastructure. They depend on specific contexts: geographical, historical and inherent characteristics of urban spatial structures. Two climate-related hazards are the most common.

One of the most dangerous phenomena caused by climate change that is occurring more and more frequently is flash flooding in cities [16]. Many scientists use MCA to identify the areas most at risk of flooding, and the method often involves an analytical hierarchy process. They develop the results using geographic information systems [17–19].

Another important phenomenon is related to the thermal characteristics of urban areas. Changes in the urban thermal environment lead to urban heat islands (UHIs) and heat waves in midsummer. The UHI is a phenomenon of heat accumulation in urban areas due to the built-in urban environment and human activities. It causes socio-economic problems such as excessive energy consumption and a high potential for heat-related illness and mortality [20]. It is considered the most obvious feature of the urban climate [21]. The UHI is an important and serious problem of the urban environment and has attracted the attention of decision makers [22]. To identify thermal hazards, researchers use statistical methods. One example is a study on the city of Aschaffenburg, for which thermodynamic urban climate model simulations were carried out [23]. The researchers calculated the air flow paths from the thermal hotspots and the cool rural areas of the city. The heat island areas of the city were determined by statistically processing the results. Areas from which cool air flowed to cool the thermal hotspots were also identified [23].

One of the approaches to identifying critical areas that pose a potential thermal risk to the population is the surface urban heat island (SUHI) [24], which can be correlated with a number of parameters that characterize potential risks to the population and infrastructure. The SUHI is determined using statistical methods and GIS-based tools to describe its extent.

Another aspect related to the impact of climate change in cities is industrialization. Industrial and post-industrial cities have specific problems that define their vulnerability, but also characteristics that offer potential for adaptation [25]. For example, brownfield redevelopment is an important measure to mitigate climate change in post-industrial areas [26]. On the other hand, urban green spaces make an important contribution to improving climate adaptation [27]. Green infrastructure (GI) is recognized as an indisputable prerequisite for resilient cities. Greening strategies can improve the urban environment by, for example, increasing people's thermal comfort and reducing the negative impacts of heat waves and flooding. The adaptation potential can be estimated using parameters based on satellite-based NDVI data.

As changes in the built urban environment reduce the cooling effect of vegetation and moist soil, it is important to better understand the complex processes at the interface of urbanization, climate and human health. For each of the methods mentioned, it is important to use a variety of high-resolution data, preferably as recent as possible, or in the case of machine learning, to use sufficient training data. This approach leads to results with a high accuracy.

Considering the methodological potential and the spatial information sources, there are possibilities to determine the vulnerability to climate-related hazards. Accordingly, the aim of this study was to adapt and test a methodological approach to determining the areas most vulnerable to climate-related hazards using the example of the post-industrial city of Knurów in Poland. This study applied a multi-criteria analysis method using the analytical hierarchy process based on GIS maps. Georeferenced parameters characterized by indices on SUHIs, green areas, flood risks and brownfields were used as a basis for the MCA. The approach was tested in the specific context of a post-industrial city. We used the post-industrial city of Knurów in Poland as our example. The approach involved dividing the city into statistical regions and applying a multi-criteria method using the analytical hierarchy process based on GIS map data.

In the case of Polish cities, it is possible to use an extensive database of statistical data (including population data), spatial and topographical data (including land use data) and other data provided by municipal offices and state institutions. An important part of the process of selecting the areas most vulnerable to climate change in a city is the decision on the choice of spatial units. In the case of Polish cities, these can be districts, statistical regions or cadastral districts. In justified cases, the division into catchment areas is used.

Section 2 describes the methodological approach taken in this study with an explanation of the selection, weighting and normalization of indicators and provides the sources and method of compiling the data used for the calculations. In Section 3, we discuss the results we obtained one by one in relation to the industrial character of Knurów. These are the hydrological hazard assessment, the green potential assessment and the thermal hazard assessment for the statistical areas. We also discuss the results of the MCA in relation to the assessed objectives and the overall objective. Section 4 provides a comparison of the method and results with the work of other researchers using the MCA and AHP. The final part of the article, Section 5, contains the conclusions.

2. Methodological Approach

In this study, we applied the analytic hierarchy process (AHP). The hierarchy consists of three levels: (1) the main goal, (2) three objectives and (3) fifteen attributes, five for each objective. The main goal is to assess the index of potential risk caused by urban climate change, which requires calculating the index of potential hydrological risk in relation to various hydrological risks (H), the index of the mitigation potential of urban greening for thermal and hydrological risks (G) and the index of potential thermal risk in relation to the risk of the population exposed to the urban heat island (T). The criteria of the first and third objectives are considered cost criteria, while the criteria of the second objective are considered benefit criteria.

To achieve the first objective (H), the following attributes were calculated:

- H1. Average sealing of soils of a given statistical district;
- H2. Percentage of the area of drainless basins in the area of a given statistical district;
- H3. Number of buildings in the areas of drainless basins and 100-year water in a given statistical district;
- H4. Number of local flooding events in a given statistical district;
- H5. Percentage of areas of 100-year water in the area of a given statistical district.

The second objective (G) consists of following attributes:

- G1. Percentage of the biologically active area in the area of a given statistical district;
- G2. Percentage of tree-shaded areas in built-up areas of a given statistical district;
- G3. Percentage of areas with an NDVI greater than 0.4 in the area of a given statistical district;
- G4. Percentage of green areas in the area of a given statistical district;
- G5. Percentage of areas with an NDMI greater than 0.2 in the area of a given statistical district.

The third objective (T) includes the following:

- T1. Number of residents in zones of elevated temperatures by statistical district;
- T2. Percentage of urban surface heat island area in the area of a given statistical district;
- T3. Percentage of the 100 m buffer area around the urban surface heat island in the area of a given statistical district;
- T4. Average surface temperature of a given statistical district;
- T5. Percentage of the area with soil sealing greater than 0% in the area of a given statistical district.

A representation of the 3-level hierarchy is presented below (Figure 1).

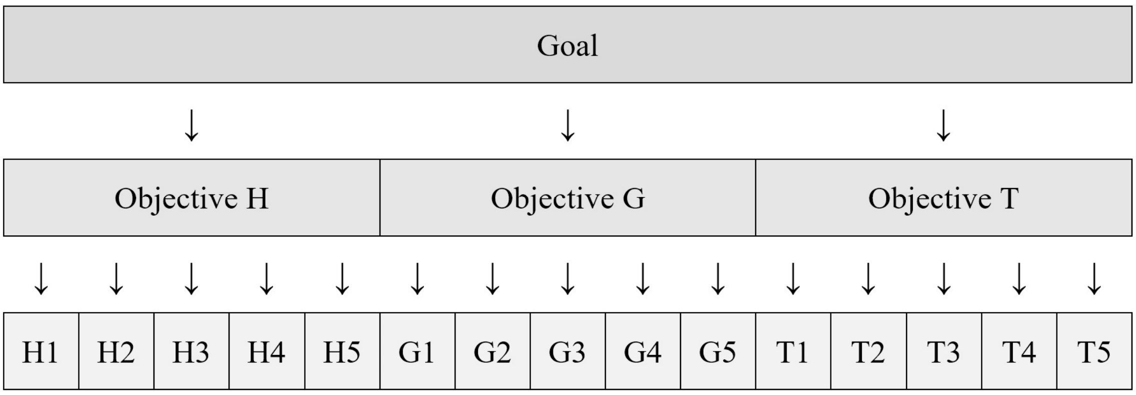

Figure 1. The three levels of the analytical hierarchy process used in the work.

In the next step, the cartographic statistical data were converted into criterion values (e.g., average soil sealing in a statistical district) and then subjected to standardization. The following formulas were used for the standardization:

$$\text{For benefit criteria, } n_{ij} = \frac{k_{ij}}{k_{max}} \tag{1}$$

$$\text{For cost criteria, } n_{ij} = 1 - \frac{k_{ij}}{k_{max}} \tag{2}$$

n_{ij}—standardized *i*-th value of *j*-th criterion.
k_{ij}—*i*-th value of *j*-th criterion.
k_{max}—maximum value of *j*-th criterion.

Since the AHP method used in the multi-criteria analysis (MCA) requires that the columns of the matrix sum to 1, after the initial standardization, additional repeat standardization was performed using the sum of the standardized values, which can be written using the following formula [28]:

$$\text{For both benefit and cost criteria, } r_{ij} = \frac{n_{ij}}{\sum_{i=1}^{m} n_{ij}} \quad (3)$$

r_{ij}—re-standardized sum of i-th value of j-th standardized criterion.

In the interpretation of the results, the higher the value of the criterion, the lower the indices of potential risk and the higher the index of the mitigation potential of greenery. The higher the value of the index, the higher the rank, where the minimum was 1 (the worst case) and the maximum was 33 (the best case). The number 33 represented the number of spatial entities being evaluated.

2.1. Applied Data

To achieve our ambitious goal, it was necessary to use different types of data from different sources. Both vector and raster data were used, all of which were free. The spatial vector data were downloaded from the Polish national geoportal [29]. These spatial data included the following: land cover (land use), buildings, river and stream network, boundaries of cadastral districts, city boundaries and boundaries of statistical districts. These data are part of the BDOT10k—Database of Topographic Objects and given at a scale of 1:10,000 [29]. The flood hazard map and the flood risk map for the INSPIRE theme Natural Hazard Zones were downloaded from the Informatic System of National Protection [30]. The theme contains spatial data on the extent of 50-, 100- and 500-year floods, i.e., the extents of floods with probabilities of 1 in 50, 100 or 500 years. The point data on local floods were obtained from the town hall in Knurów. The Polish national geoportal (geoportal.gov.pl, accessed on 15 March 2024) was also the source of the raster data of the digital elevation model as well as the LIDAR data used to create a tree map. We used raster data from the Landsat 8 satellite (USGS) and the Sentinel-2 satellite (ESA) as well as raster data on Imperviousness Density 2018, which are accessible via the Eyes On Earth platform of Copernicus Europe. In addition to spatial data, statistical data were also used, in particular, population data from the local database of Polish statistics [31]. All data underwent special transformation and processing to produce the above-mentioned criteria maps.

For the development of the urban heat island map, we used data from Landsat 8, which were subjected to the procedure described in Bronder et al. (2019) [32].

2.2. Study Area

The study area is the city of Knurów, which is located in the Silesian Voivodeship in southern Poland. It has an area of 33.95 square kilometers and had a population of 37,801 in 2020 [33]. The population density at that time was 1057 people per square kilometer [33]. The city is located in the Silesian Upland, which consists of two different mesoregions. The northeastern part belongs to the Katowice Upland, while the southwestern part is located on the Rybnik Plateau [34].

Knurów has around 120 years of coal mining history, which not only influenced the development of the city but also led to the creation of huge coal heaps in the immediate vicinity of two coal mines: Knurów and Szczygłowice [35,36]. Despite its industrial character, almost half of the city area is covered with forest, which dominates the southern part of the city (BDOT10k) (Figure 1). The northern part is the most urbanized part of the city, with multi-family and single-family houses (Table 1).

Table 1. Percentages of land use classes and average soil sealing, and mean temperatures of the land use classes.

Id	Land Coverage	Land Use Area in %	Mean Soil Sealing in %	Mean Surface Temperature in °C
1	multi-family housing	4.00	41.06	29.03
2	single-family housing	8.42	28.86	27.88
3	industrial and storage buildings	2.61	56.67	29.41
4	commercial and service buildings	1.03	62.35	29.45
5	other buildings	1.21	47.35	29.01
6	land under a vehicular road	3.26	46.40	27.76
7	land under the rail track	1.50	31.61	28.40
8	land under the vehicular road and rail track	0.02	4.98	25.44
9	square/plaza	1.33	50.08	28.42
10	landfill site of industrial waste	1.88	0.62	31.94
11	coal waste heap	10.82	3.66	31.52
12	land under technical facilities or structures	0.70	34.31	27.98
13	other land not in use	0.02	0.00	24.50
14	industrial and storage area	0.62	55.75	29.53
15	shrubs	0.27	7.92	26.97
16	grassland vegetation	16.03	5.61	26.78
17	cultivation on arable land	8.88	1.06	26.34
18	allotment gardens	2.16	16.27	27.03
19	orchard	0.09	5.34	27.13
20	forest tree nursery	0.01	4.26	27.14
21	decorative plant nursery	0.02	17.40	28.33
22	woods	44.78	0.22	23.88
23	grove	1.81	0.10	25.56
24	woodland	1.99	3.35	27.60
25	flowing water	0.18	0.00	28.38
26	water bodies	3.64	3.52	25.03

Source: Authors' calculations based on BDOT10k, Landsat and EEA data.

According to our research based on BDOT10k data, landfills, mainly for coal waste, cover about 12.7% of the urban area. The residential area is about the same size (12.4%). Grasslands, forests and shrubs cover about 65% of the urban area (Figure 2).

Our analysis of the numerical terrain model of Knurów showed that the average elevation of the city is 243.6 m above sea level and that the Central Mine Dump is 285.3 m above sea level. The lower-lying areas are located in the western part of the city.

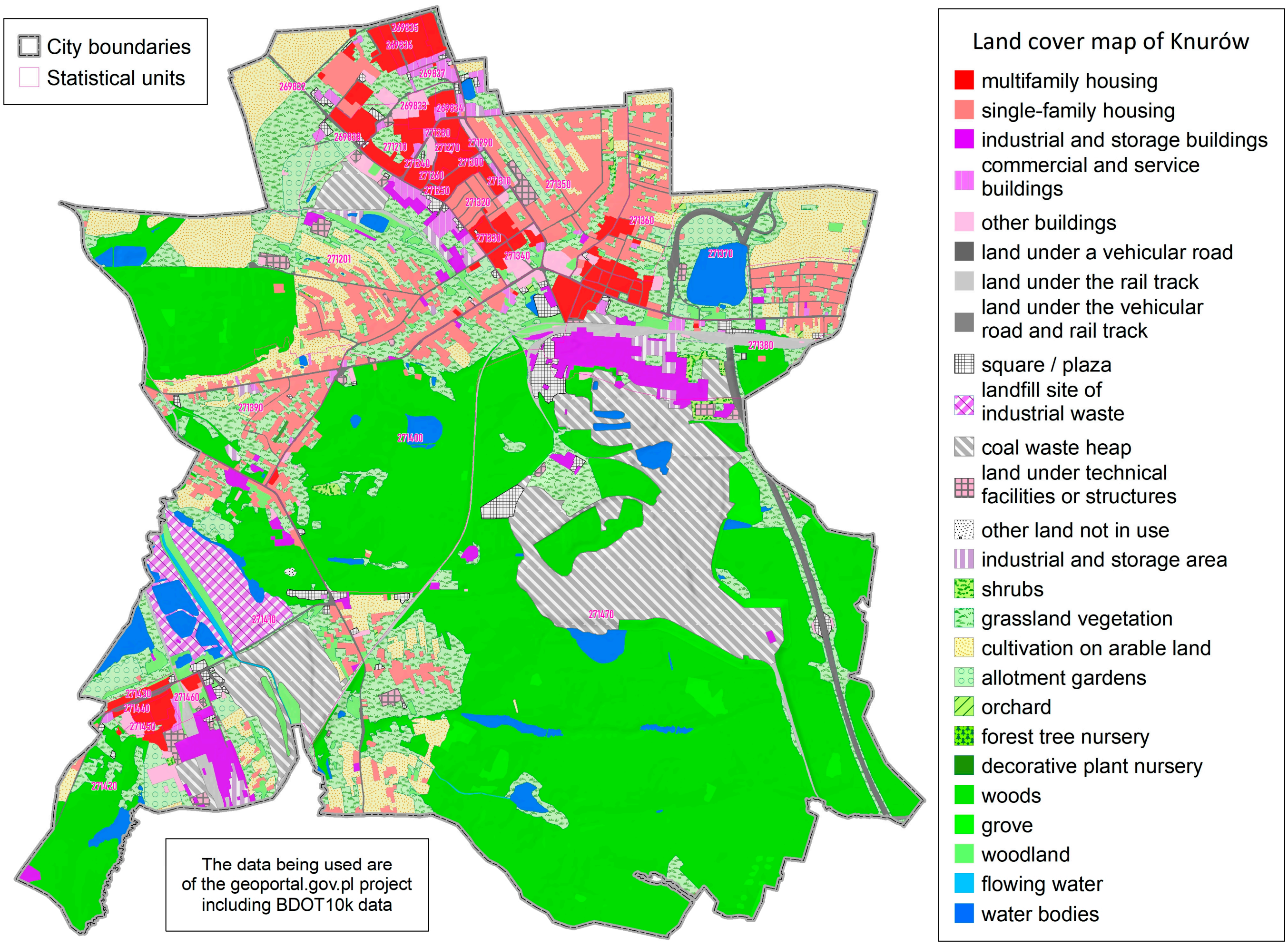

Figure 2. Map of land cover in the Knurów municipality.

The morphology of the mining areas has changed considerably over more than a century of mining. The progressive subsidence of the area has led to hydrological and hydrogeological changes and the destruction of numerous building structures. These changes have led to flooding and structural damage to buildings and anthropogenic surface water bodies [37]. It has been predicted that ground deformations will lead to significant waterlogging and subsequent permanent flooding [38]. Those phenomena are currently occurring on a significant scale in the city [39].

Anthropogenic pollution, which is closely related to the industrial character of Knurów, is the cause of surface water pollution. The main sources of pollution include the discharge of saline groundwater from mines and the leaching of mining waste dumps. Knurów is located within 4 surface water bodies (RW600019115899 Bierawka from Knurówka to the mouth, RW600061158329 Potok Szczygłowicki, RW60006115838 Bierawka up to and including Knurówka, RW600061162299—Jasienica up to and including Ornontowicki Potok), which are continuously monitored as part of the state environmental monitoring program [39].

The negative effects have spread not only to residential areas and bodies of water but also to large areas of forest. Significant changes in forest areas have been observed, which have played out to varying degrees at the beginning of the 21st century [40]. In the 1990s, it was predicted that land subsidence in the Knurów region could reach 40 m by 2030–2050 [41]. The deformation of the ground is currently so great that the land remains considerably deformed despite intensive reclamation work. It is possible to reduce the deformation through work that minimizes the impact of coal mining [42]. However, the land deformation is getting worse [43]. A study from 2022 predicts 21 drainless basins reaching a depth of 10 m [44].

Currently, the city council has set the revitalization and rehabilitation of degraded areas and post-mining landscapes as one of its urban policy goals [36]. Among the relevant measures being taken are environmental rehabilitation and the delineation of natural areas under protection. They assume that it is necessary to introduce vegetation areas and greening of the areas demarked for recultivation [36].

The climate of Knurów is defined on the Köppen and Geiger scale as Dfb, which is a continental climate with warm summers [45]. It is distinguished by the highest number of days with very warm weather with precipitation. The frequency of days with moderately warm weather with high cloud cover and precipitation is also the highest [46].

2.3. Spatial Division of the City of Knurów

The city of Knurów can be divided into three cadastral districts: Knurów, Krywałd and Szczygłowice. However, these are too broad to accurately determine the areas where action is required. Therefore, it was decided that for the assessment of the potential risk index, which describes the potential risk to the city caused by climate change, the division into statistical districts would be used (Figure 3).

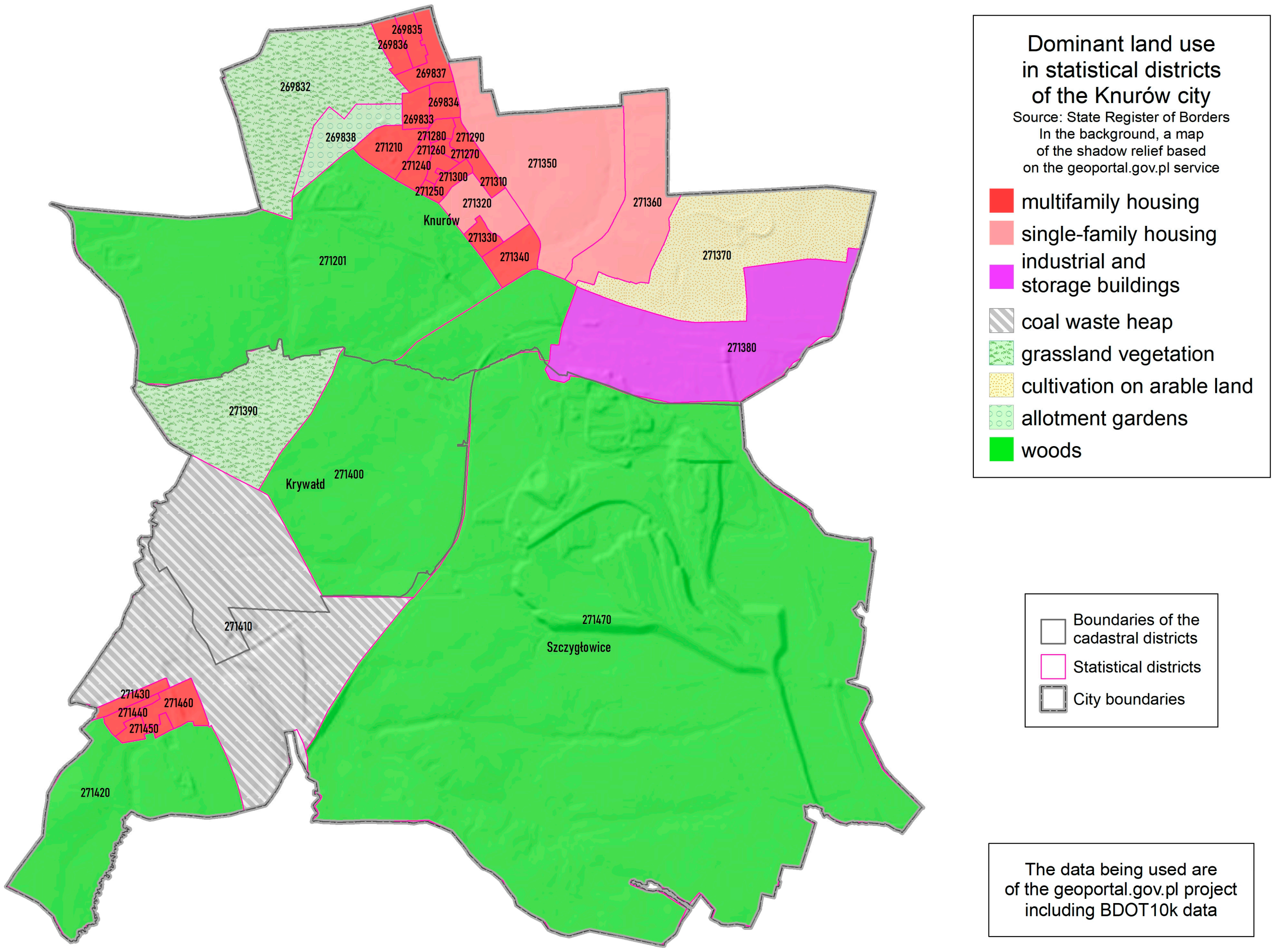

Figure 3. Spatial division of the Knurów municipality into statistical districts, with the dominant land use in each district.

A statistical district is a territorial unit for aggregating statistical data, consisting of a maximum of nine census districts. The size of the statistical district is defined in such a way that it may not be larger than 2700 persons or 999 housing units [47].

There are 33 statistical districts in the city of Knurów, and the multi-criteria analysis was carried out for these districts. The map below shows the spatial division of the city of Knurów into statistical districts, supplemented by the predominant land use within each district. We can see that there are only 8 dominant land use classes (Figure 3).

3. Results

3.1. Land Use versus Soil Sealing and Land Surface Temperature

Land use (land cover) is linked to soil sealing and surface temperature. The type of land use and the degree of soil sealing may lead to an increased temperature of the ground surface. In some areas where soil sealing is high enough, urban heat islands are created. Paved impermeable surfaces combined with unfavorable drainage conditions favor flooding. In the city of Knurów, the highest degree of soil sealing, averaging over 50%, is associated with commercial and service buildings, industrial and warehouse buildings, industrial and storage areas and squares. Values of between 40% and 50% are achieved by land under a road, apartment buildings and other buildings. Land under technical facilities or buildings and land under railroad tracks achieve soil sealing values of between 30% and 40% (Table 1).

In terms of average surface temperatures, landfills (31.9 °C), coal waste piles (31.5 °C), industrial and storage areas (29.5), commercial and service buildings (29.4 °C), industrial and service buildings (29.4 °C), apartment buildings (29.0 °C) and other buildings (29.0 °C) reached temperatures of at least 29 °C. The average surface temperature calculated for the entire city is 26.5 °C.

On the other hand, the temperatures of farmland, groves, water bodies, other unused areas and forests are below the urban average. Forests, which make up 44% of the city area, are characterized by the lowest average temperature of 23.9 °C (Table 1).

3.2. Pairwise Comparison and Calculation of Weights

To determine the importance of one goal over another and one attribute over another, we used the method of pairwise comparison [48]. In a pairwise comparison, experts assign their own preferences for all possible pairs of goals and attributes. Preferences are expressed on a 9-point scale, and 1 to 1 means equal importance, while 9 to 1 means extreme importance of one attribute over another attribute, with intermediate values in between.

The preferences were used to calculate the weights for the second and third levels of the hierarchy. When calculating the weights, a consistency factor was also calculated to ensure the consistency of the preferences. The procedure is described by Malczewski [49], among others. The matrix below shows the preference allocation of the goals within the main goal (Figure 4).

O	H	G	T
H	1	1/2	1/3
G	2	1	1
T	3	1	1

Figure 4. The pairwise comparison matrix for objective weights—2nd hierarchy level.

The set of 3 matrices below presents the preference assignment of attributes within the 3 objectives (Figure 5).

H	H1	H2	H3	H4	H5	G	G1	G2	G3	G4	G5	T	T1	T2	T3	T4	T5
H1	1	1	1/2	1/2	2	G1	1	1/3	1/3	5	1/2	T1	1	3	3	2	3
H2	1	1	1/2	1.2	4	G2	3	1	2	5	2	T2	1/3	1	2	1/2	3
H3	2	2	1	1	4	G3	2	1/2	1	5	1	T3	1/3	1/2	1	1/4	2
H4	2	2	1	1	3	G4	1/5	1/5	1/5	1	1/5	T4	1/2	2	4	1	5
H5	1/2	1/4	1/4	1/3	1	G5	2	1/2	1	5	1	T5	1/3	1/3	1/2	1/5	1

Figure 5. The pairwise comparison matrixes for attribute (criteria) weights—3rd hierarchy level.

In this way, sets of weights relating to three objectives and 15 attributes were calculated (Figure 6).

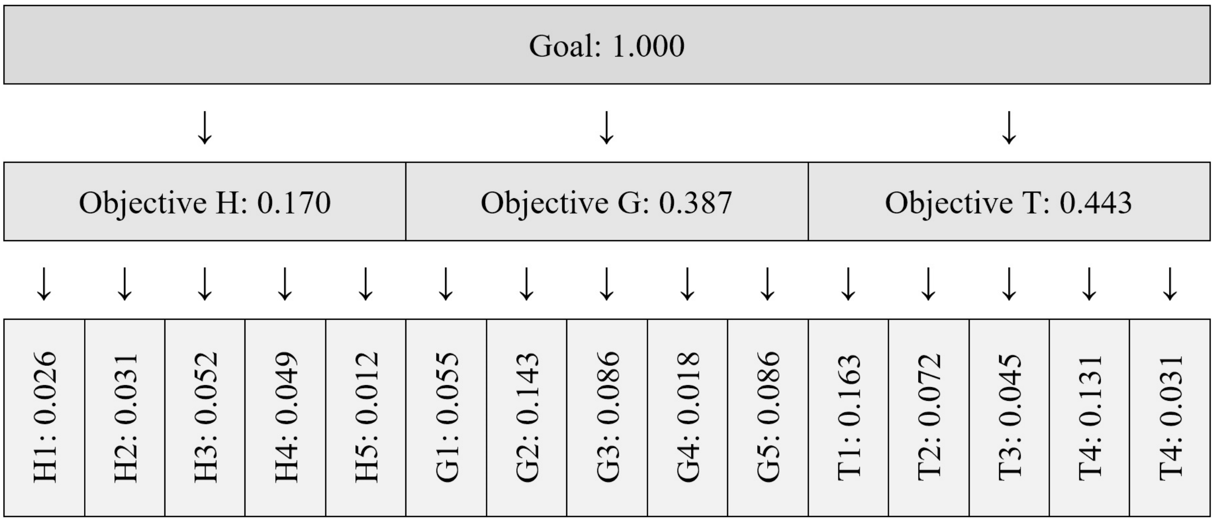

Figure 6. Calculated weights for the three levels of the analytical hierarchy process.

All the results obtained from the weight calculations met the condition of consistency. Based on the results of the analysis, the index of potential thermal risk was identified as the most important in the expert assessment (0.443). The second most important for the city of Knurów was the index of the mitigation potential of urban greenery (0.387) due to the size of biologically active areas, including the significant size of forest in Knurów. The index of potential hydrological risk, which describes hydrological risks, was the least important for the city (0.170). Experts decided that the index of potential thermal risk and the index of the mitigation potential of urban greenery were most important for this industrial city.

Of the 15 attributes, T1 (number of inhabitants in zones with elevated temperatures by statistical district) with a value of 0.163, G2 (percentage of total tree-shaded area of built-up areas within a statistical district) with a value of 0.143 and H3 (number of buildings in the areas of drainless basins and 100-year water within a statistical district) with a value of 0.052 were the most meaningful.

3.3. *Results of the Analyses*

Table 2 shows the results of the calculation of the standardized and weighted scores for the four variables (objectives): the index of potential hydrological risk (H), index of the mitigation potential of urban greening, (G) index of potential thermal risk (T) and sum of the three. The table also contains the results of four rankings (Table 2).

Table 2. Assessment of the hydrological and thermal potential risk indices, index of greenery potential within statistical districts and results of rankings of statistical regions.

S. Districts	∑H1...H5	Rang	∑G1...G5	Rang	∑T1...T5	Rang	∑HGT	∑Rang
269832	0.0329	27	0.0288	10	0.0306	18	0.0303	21
269833	0.0318	19	0.0263	13	0.0331	20	0.0302	20
269834	0.0301	12	0.0166	28	0.0278	16	0.0238	14
269835	0.0311	16	0.0167	27	0.0273	15	0.0238	13
269836	0.0308	14	0.0124	32	0.0347	21	0.0254	15
269837	0.0295	11	0.0102	33	0.0260	14	0.0205	9
269838	0.0263	5	0.0263	12	0.0163	9	0.0219	11
271201	0.0246	4	0.0651	4	0.0555	31	0.0540	30
271210	0.0164	1	0.0254	16	0.0189	10	0.0209	10
271240	0.0292	10	0.0195	25	0.0077	1	0.0159	1
271250	0.0339	29	0.0326	9	0.0206	12	0.0275	17
271260	0.0320	24	0.0259	15	0.0103	4	0.0200	8
271270	0.0285	8	0.0207	23	0.0138	7	0.0190	7
271280	0.0322	25	0.0402	6	0.0195	11	0.0297	19
271290	0.0288	9	0.0157	29	0.0123	6	0.0164	2
271300	0.0318	18	0.0214	22	0.0100	3	0.0181	6
271310	0.0301	13	0.0149	30	0.0249	13	0.0219	12
271320	0.0319	21	0.0200	24	0.0283	17	0.0257	16
271330	0.0320	23	0.0231	20	0.0371	23	0.0308	22
271340	0.0315	17	0.0243	18	0.0405	26	0.0327	26
271350	0.0234	3	0.0251	17	0.0400	25	0.0314	24
271360	0.0325	26	0.0236	19	0.0395	24	0.0322	25
271370	0.0330	28	0.0354	7	0.0510	29	0.0419	28
271380	0.0208	2	0.0266	11	0.0321	19	0.0281	18
271390	0.0358	31	0.0470	5	0.0529	30	0.0477	29
271400	0.0369	33	0.0888	1	0.0649	33	0.0694	33
271410	0.0318	20	0.0352	8	0.0438	27	0.0384	27
271420	0.0354	30	0.0735	3	0.0470	28	0.0553	31
271430	0.0319	22	0.0260	14	0.0356	22	0.0312	23
271440	0.0310	15	0.0143	31	0.0156	8	0.0177	5
271450	0.0277	6	0.0186	26	0.0109	5	0.0167	3
271460	0.0278	7	0.0222	21	0.0096	2	0.0176	4
271470	0.0366	32	0.0774	2	0.0618	32	0.0636	32
Sum	1.0000	-	1.0000	-	1.0000	-	1.0000	-

Source: Authors' calculations.

The spatial distribution of the analysis results is also shown in the maps in Figures 7–10. The description of the results shows only the lower part of the distribution, that is, the first quantile of the data (up to 25% of the data).

3.3.1. Assessment of the Index of Potential Hydrological Risk for Statistical Districts

The lowest scores of the potential hydrological risk index refers to the following statistical districts: 271210, 271380, 271350, 271201, 269838, 271450, 271460, 271270 and 271290. The average score of the hydrological risk index for these nine statistical districts was 0.025, the minimum was 0.016 and the maximum was 0.029 (Figure 7). In five cases of the statistical districts, the predominant land use class was multi-family dwellings and, in four cases (with one case each), the predominant classes were single-family dwellings, industrial and storage buildings, allotments and forests, respectively. In the northeastern part of the city, the hydrological risk was caused by the large number of drainless basins. In the southwestern part of the city, buildings were at risk because they were located in a zone with a 1% risk of flooding.

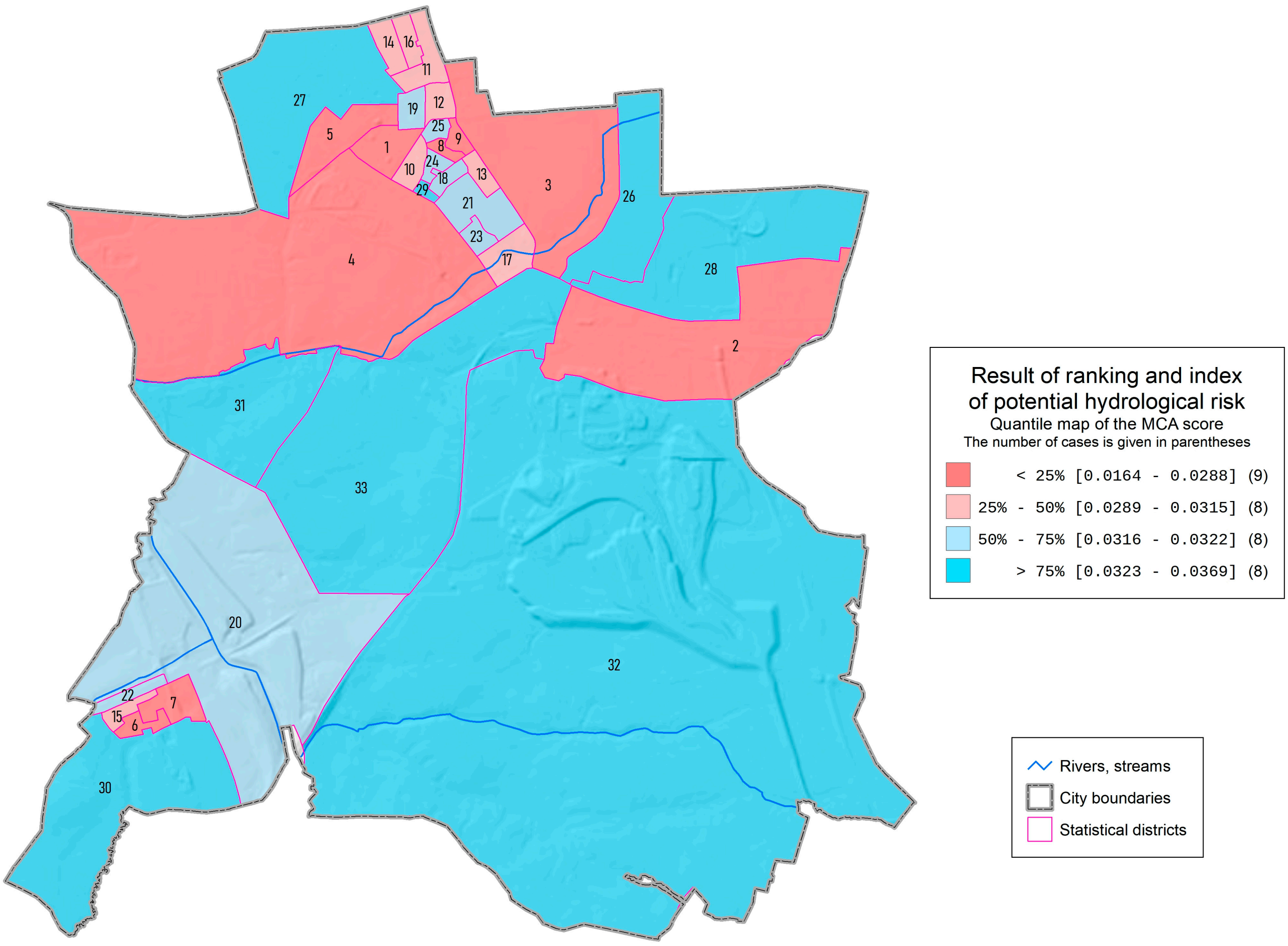

Figure 7. Quantile map of the index of potential hydrological risk.

3.3.2. Assessment of the Index of the Mitigation Potential of Urban Greenery for Statistical Districts

According to the results, the index of the reduction potential of urban greenery was lowest in the intensively built-up area, i.e., in the city center of Knurów (northern part of the city) and in the southwestern part of the city, near the Knurów-Szczygłowice coal mine. The first quantile was represented by nine statistical districts. These are: 269837, 269836, 271440, 271310, 271290, 269834, 269835, 271450 and 271240. The average score of the urban green mitigation potential index for the nine statistical districts listed above was 0.015, the minimum was 0.010 and the maximum was 0.019 (Figure 8). In all nine statistical districts, the predominant land use class was multi-family residential (Figure 3). On the other side of the statistical distribution, there was one value outside and three values far outside. These values, in contrast to the previous nine, represented a very favorable condition and a high index of urban green space mitigation potential. In all four statistical districts, the predominant land use class was forest.

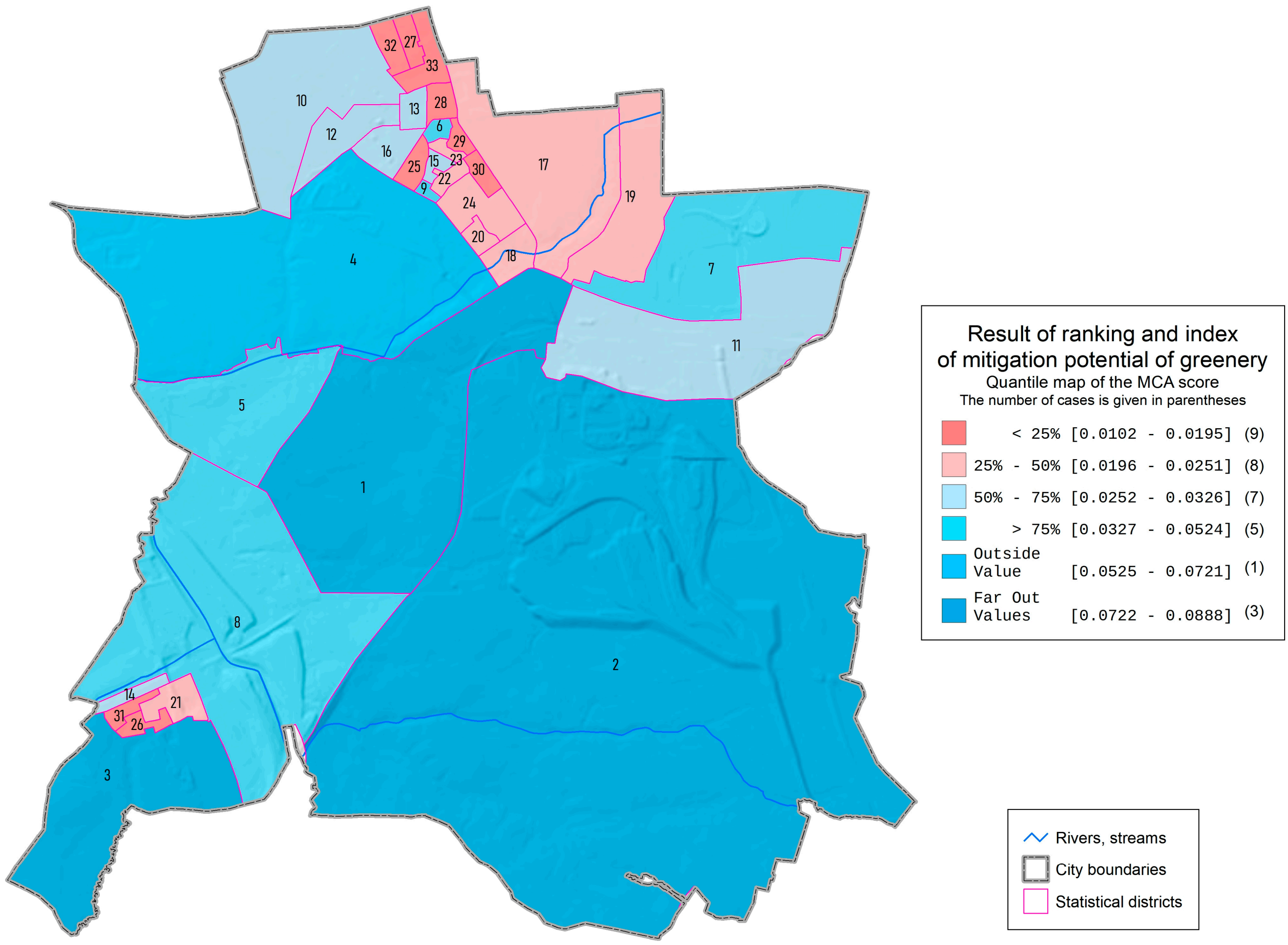

Figure 8. Quantile map of the index of the mitigation potential of urban greenery.

3.3.3. Assessment of the Index of the Potential Thermal Risk for Statistical Districts

The results of the potential thermal risk index in terms of spatial distribution were similar to the results of the green space mitigation potential index. The first quantile (up to 25% of the results) consisted of nine statistical regions: 271240, 271460, 271300, 271260, 271450, 271290, 271270, 271440 and 269838. The average score of the potential thermal risk index for these nine statistical districts was 0.012, the minimum was 0.008 and the maximum was 0.016 (Figure 9). The predominant land use class in eight of the nine statistical districts was multi-family residential. In only one district, ranked ninth, the predominant land use class was allotments (26.64%), but the second most common class in this district was multi-family residential, accounting for 26.41% of the district's land area (Figure 3).

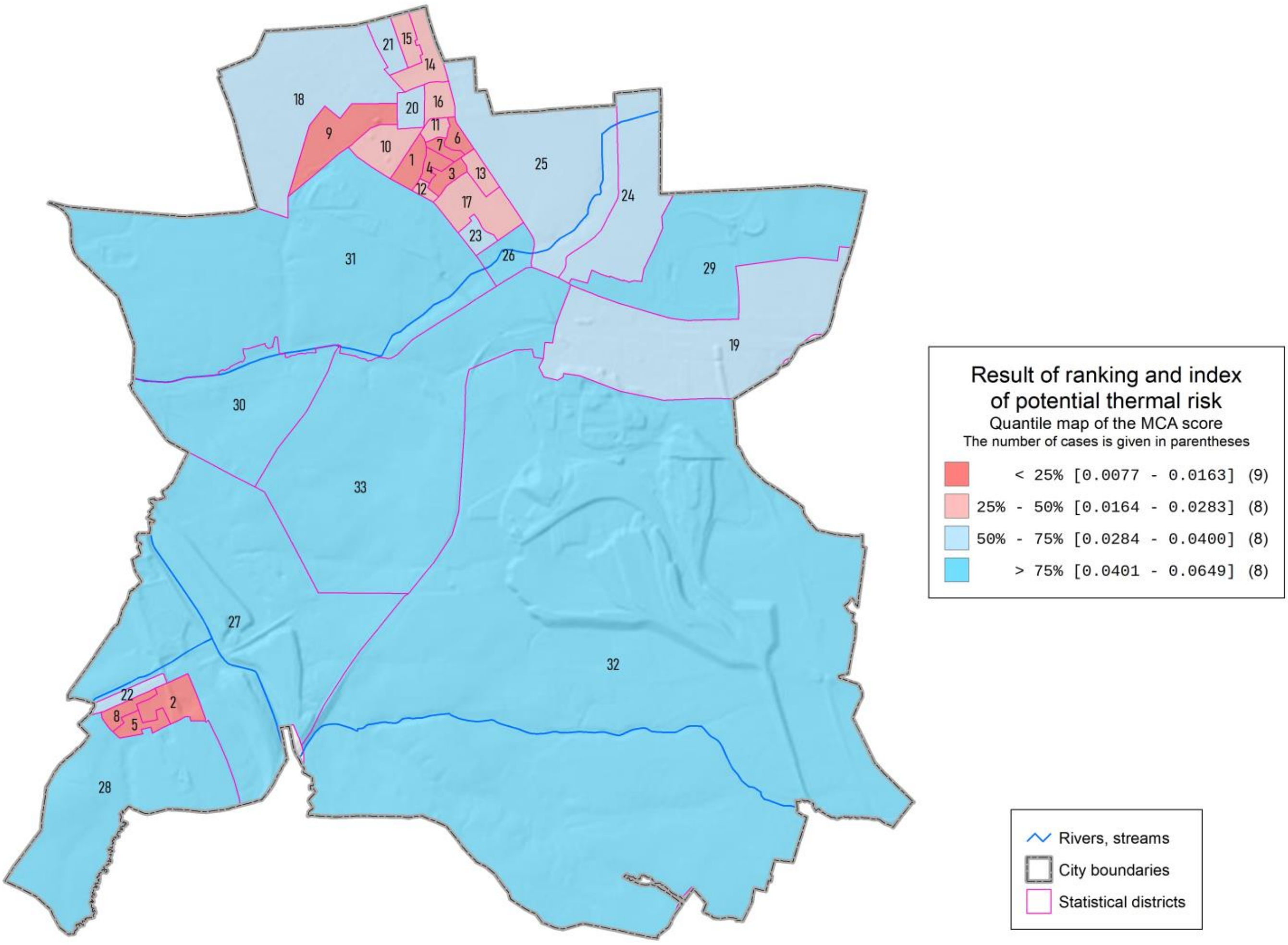

Figure 9. Quantile map of the index of potential thermal risk.

The number of inhabitants living in zones with elevated temperatures (the urban heat island and the 100 m buffer around it) in the areas of the nine statistical regions mentioned above was 8730, which represented 23.1% of the total population of the city. The remaining 7017 inhabitants living in zones with elevated temperatures were located in 21 other statistical regions. About 41.7% of the city's inhabitants lived in zones with elevated temperatures.

3.3.4. Results of the MCA in Relation to the Assessed Objectives and the Overall Goal

The final step of the analysis was to aggregate the results of the three previously described steps. The weights calculated for each objective were used in the aggregation. In this step, we obtained the final ranking of the statistical districts in terms of the aggregated potential risk indices (hydrological and thermal) and the urban green space mitigation potential index. As in the previous cases, the first quantile (up to 25% of the results) consisted of nine statistical regions: 271240, 271290, 271450, 271460, 271440, 271300, 271270, 271260 and 269837. The nine regions were located in the city center of Knurów (northern part of the city) and in the vicinity of the Knurów-Szczygłowice coal mine (southwestern part of the city). The average value of the potential thermal risk index for these nine statistical districts was 0.018, the minimum was 0.016 and the maximum was 0.020 (Figure 10). In all nine statistical districts, the predominant land use class was multi-family housing (Figure 3).

The final results showed that the most vulnerable areas in Knurów were the areas with intensive development in the city center and in the southwestern part of the city. These areas were the most vulnerable to the two analyzed risks and had the lowest mitigation potential for urban greenery. This constituted a precise delineation of the areas where adaptation measures to the negative effects of climate change are urgently needed.

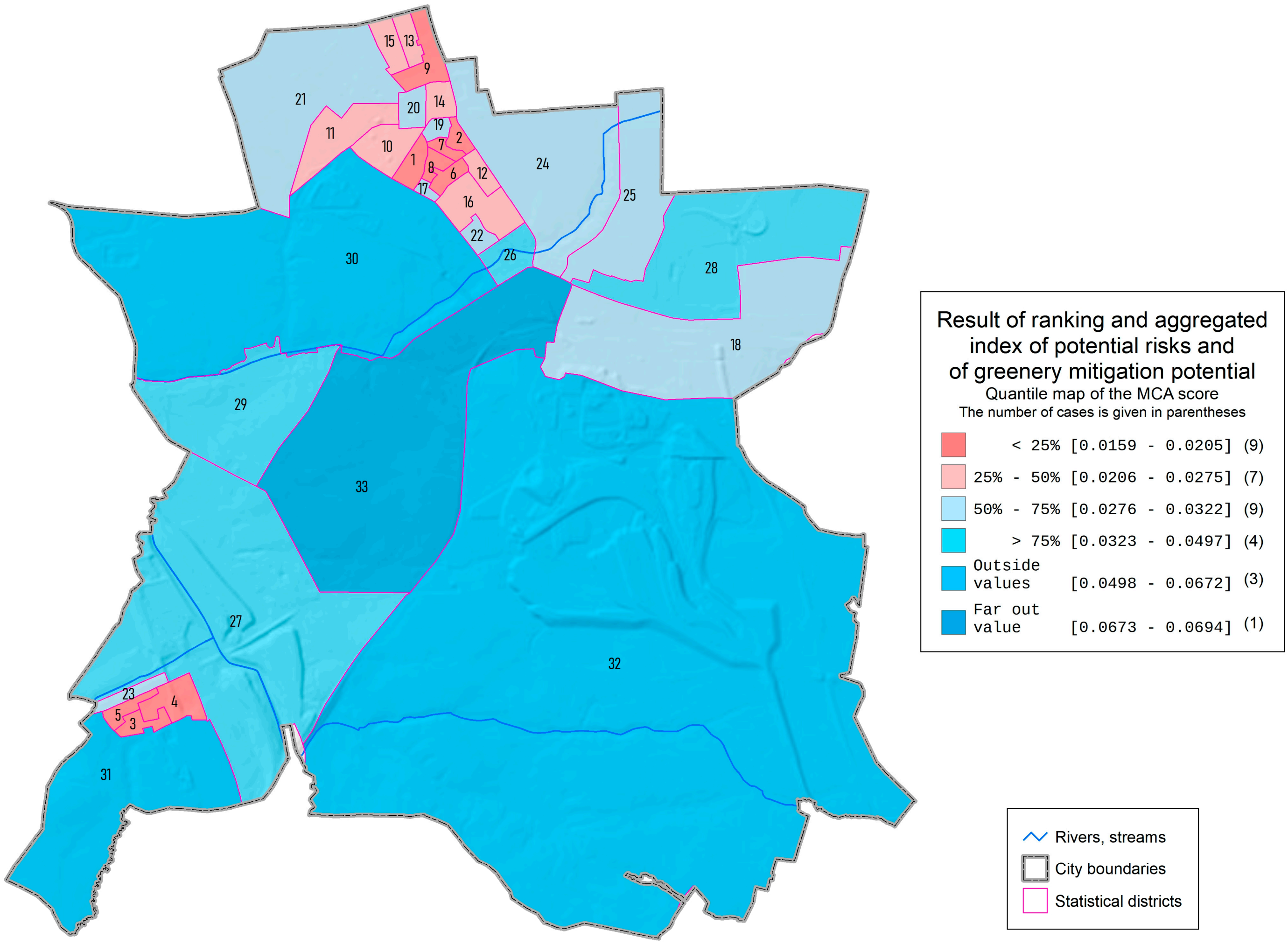

Figure 10. Quantile map of the aggregated index of potential risks and of the greenery mitigation potential.

The methodology applied was primarily used to categorize areas according to the urgency of implementing adaptation measures. It is particularly useful when cities are developing urban adaptation plans or other related initiatives or action plans. It is then possible to localize fairly precisely the systemic solutions in a larger area that neutralize the effects of a particular climate threat (depending on the size and number of subdivisions used for the study).

4. Discussion

Numerous studies reported in scientific journals deal with the delineation of climate-sensitive areas but consider only one hazard, e.g., the thermal hazard associated with an above-ground urban heat island [16,50–52] or the flood hazard associated with the presence of rivers or numerous drainless catchments. It is possible to limit oneself to analyzing a single hazard, but the climate is a complex phenomenon. Furthermore, it is important to contrast the hazard factors with the factors that can mitigate the consequences and significantly influence the results. For this reason, our study analyzed three targets—two threats and one mitigating factor. Fifteen criteria on two levels of the analytical hierarchy process were analyzed.

According to the subdivision into three objectives, five criteria were compared in pairs. This was appropriate as the number of attributes to be compared did not exceed 7 ($\pm$2) [53].

Saaty, the author of the AHP method, proposes that only a limited number of criteria can provide precise results for the analysis. Accordingly, the 15 criteria in our study were appropriate for weighing the three objectives. The more indicators, the more difficult it is to achieve a uniform weighting [49].

Research on industrial and post-industrial cities often focuses on studying the degree of degradation of green spaces [54–56]. Trees play a role in temperature reduction in cities [57–59] and, in our study, the percentage of the areas shaded by trees in built-up areas within a statistical district in Knurów showed a high value, which was a positive finding. This can be further analyzed by determining which tree species are suitable for which types of areas according to current knowledge [54]. Such work is important because different conditions may exist in parking lots (need for tall trees to allow parking for cars) and on roads (suitable species to shade the road surface but not overshadow the lowest floors of buildings). Research should particularly take into account the climatic conditions and the tree species present in the region in order to increase the positive mitigating effect of greenery in its cities.

In the city of Knurów, there are numerous drainless basins created by mining and others created during urban development. The analysis carried out showed that, as part of future adaptation measures, it is important to look for solutions in the study areas, which are characterized by the presence of drainless basins, high population densities and built-up areas. The aim of adaptation measures should be to protect existing infrastructure from the negative effects of urban flooding.

Since there are no runoff-free basins near areas with a 1% probability of river flooding, it makes sense to utilize the potential of runoff-free basins to capture and store excess water during flood periods. The analyses carried out showed that it is justified to combine the retention potential of drainless basins with solutions based on green infrastructure.

Problems of water quality should be taken into account. In the event of flooding at contaminated sites, the water must be monitored. To this end, innovative optical instruments can be used to diagnose water quality in real-time without the need for traditional sampling and physico-chemical laboratory analysis [60].

The results of the analysis should be interpreted in relation to both the existing state and the projected threats of future climate change, especially with regard to thermal conditions and also factors influencing hydrological conditions. Natural conditions, economic changes and urban development plans are also important in this context.

Our analyses and calculations showed that the impact on the city varied depending on the type of development and the concentration of buildings and population. Measures to limit the impact of the urban heat island should be differentiated according to the local situation described by the index of potential thermal risk. Given the uncertainty of the assessment and, in particular, the projected intensification of unfavorable temperature phenomena, it makes sense to use the SUHI areas together with a certain buffer as a basis for adaptation measures.

A phenomenon of increased temperature was found to be occurring at the local level, especially in industrial and post-industrial areas and in public service areas (recreational areas, schools and commercial areas (shopping centers and supermarkets)). Unfavorable effects of these types of land developments on the surrounding residential areas were also usually observed. Therefore, it is justified to act in places characterized by a high index of potential risk when that index summarizes various factors, including the concentration of buildings and other sealed surfaces (parking lots, playgrounds, artificial surfaces) as well as a high population density.

At the level of the entire city, the mining dumps in Knurów, which are an important source of heat due to the physical properties of coal waste, play an important role in shaping the thermal conditions in the city. On the other hand, the post-industrial areas underwater provide a positive cooling effect. Therefore, it makes sense to adequately develop the areas experiencing the pressure of mining activities in order to minimize the negative effects (reclamation) and enhance the positive effects (development of floodplains as an element of blue-green infrastructure).

The proposed methodological approach using MCA for spatial indicators proved to be a useful tool for delineating areas of potential risk due to climate change in the city. The approach analyzed key environmental characteristics that represent aspects of both hazard assessment and adaptation potential.

The approach provides useful information for urban climate adaptation planning that takes into account the specific context of industrial activities, which have impacts that are particularly visible in land subsidence processes (flood risk) and effects of coal mining dumps (heat generators).

5. Conclusions

Knurów is an example of a city whose main thermal factor is an area with intensive multi-family housing development, industry, a coal dump and large-scale retail and service activities. Additionally, intensive mining activities in the area have led to the development of drainage basins that make up 1% of the city's area. The accumulation of multiple problems within the city prompted the development in this study of a methodology to identify the areas most affected by the negative impacts of climate-related hazards in the city. Satisfactory results were obtained, which made it possible to identify particularly vulnerable zones where adaptation measures are required and to classify the zones according to the urgency of remedial action. The developed methodology is universal in nature and can be usefully applied in the city's strategizing, especially when developing climate change adaptation plans, to support the prioritization of mitigation measures and for the identification of the areas most vulnerable to thermal and hydrological hazards or with the least developed green infrastructure.

Out application of the proposed methodological process generated useful information for the city's climate adaptation planning, taking into account the specific characteristics of the city, such as the existing industrial activities (especially coal mining, which leads to land subsidence and flooding hazards), the existing brownfields and the impact of the central coal dump as a heat generator.

The use of precise data and spatial information organized in a geographic information system was fundamental for the calculation of the criteria values that were subsequently applied in the multi-criteria analysis.

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