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Geospatial Prioritization of Terrains for "Greening" Urban Infrastructure

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Abstract: This study aims to scientifically justify the identification of suitable urban properties for urban green infrastructure (UGI) interventions to optimize its natural regulating functions for long-term pollution mitigation and secondary dust reduction. This study adheres to the perception that planning urban transformations to improve ambient air quality (AQ) requires a thorough understanding of urban structural heterogeneity and its interrelationship with the local microclimate. We apply an approach in which UGI and its potential multifunctionality are explored as a structural–functional element of urban local climatic zones. The same (100 × 100 m) spatial framework is used to develop place-based adapted solutions for intervention in UGI. A complex geospatial analysis of Burgas City, the second largest city (by area) in Bulgaria, was conducted by integrating 12 indicators to reveal the spatial disbalance of AQ regulation' demand and UGI's potential to supply ecosystem services. A total of 174 municipally owned properties have been identified, of which 79 are of priority importance, including for transport landscaping, inner-quarter spaces, and social infrastructure. Indicators of population density and location of social facilities were applied with the highest weight in the process of prioritizing sites. The study relies on public data and information from the integrated city platform of Burgas, in cooperation with the city's government. The results have been discussed with stakeholders and implemented by the Municipality of Burgas in immediate greening measures in support of an ongoing program for Burgas Municipality AQ improvement.

Keywords: air pollution; urban ecosystem services; green infrastructure; local climate zones; sustainable urban planning; Burgas city

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1. Introduction

The growth of urban populations [1] and urban sprawl [2] presents us with some of the most serious challenges in maintaining our living environment and health. The degradation of natural ecosystems that accompanies urban densification poses a growing threat to the long-term provision of many of the ecosystem services that are vital to urban populations [3] and permanently limits the resilience of cities to climate change [4].

The concept of ecosystem services (ESs) has been attracting growing interest in the scientific milieu and in the arena of policymaking over the last 20 years [5,6]. ESs are related to operational concepts such as Green Infrastructure (GI), Nature-based Solutions (NBSs), and Ecosystem-based Adaptation (EbA). The impact of urban parks on human well-being and thermal comfort has been investigated by a considerable number of studies for diverse climatic conditions [7–10]. Managing the desired benefits of urban green spaces has been the subject of in-depth discussions in urban management and planning policies [11–14], where interventions in NBSs find a logical place [15]. NBSs are most clearly oriented towards providing solutions to complex challenges, in terms of urban structure and functionality, and can be seen as a sufficiently flexible approach to urban planning, in building on approaches to urban greening [16]. However, the latter requires a proper understanding of urban challenges in their local context to find an adequate response by stimulating the provision of ecosystem services [17,18]. Research in this regard offers an expanding interdisciplinarity and adheres to a systems perspective that approaches urban sustainability as a complex phenomenon [14].

Urban green infrastructure (UGI) is part of urban morphology and has an important structuring significance for the development of urban spaces in terms of the desired heterogeneity of the urban environment. This is explained by the main regulating and supporting ecosystem functions and benefits of UGI in providing a favorable quality of living environment for people. However, research shows that the relationship between green spaces and ecosystem services provided is not straightforward and is dependent on urban typology [19–21]. In their comparative analysis of sets of urban typologies and associated ecosystem service packages in temperate and tropical climate cities, Adrienne Grêt-Regamey et al. 2020 [3] find that the supply of urban ESs does not increase linearly with greenspace coverage, but is strongly dependent on urban form. In built-up neighborhoods, the proportion of trees in the total green cover is essential for maintaining regulating ESs, but in terms of microclimate, this regulation depends on the size of the built-up area. The authors emphasize that medium-height open neighborhoods synergistically support the provision of regulatory services, including microclimate regulation and air pollution control. Research by Balzan et al. 2021 [22] in the ecological conditions of a Mediterranean city shows that the capacity of ESs is highest in the urban periphery and lowest in dense urban cores. Public gardens have low ecosystem service regulation capacity, in contrast to private gardens and urban trees, which have the highest ecosystem service regulation capacity per unit area. UGI is an important tool for cities to adapt to climate change, but there is still a lack of knowledge about the optimal planting design for urban spaces and its impact on outdoor thermal comfort [10]. With the advent of new and increasingly precise and accessible geospatial technologies, new opportunities are opening up for UGI displacements based on their integrated use, and this is one of the main objectives of the present study. There is an obvious lack of more practical, geodata-driven knowledge in this field. Another important point that is addressed in this work relates to the use of already established approaches to study key aspects of the urban environment, as in the case of LCZs, which are used in urban climatology and also in the present UGI study, in accordance with the principles of spatial autocorrelation. We see here a strong potential for the application of a scientific approach in which UGI and its potential multifunctionality are explored as a structural-functional element of urban local climatic zones. They are a well-established approach in the analysis of urban morphology-urban microclimate causal relationships and, in our view, can provide a successful spatial framework for developing a place-based adapted strategy for intervention in UGI.

The construction and purposeful maintenance of green spaces in Bulgarian cities have good traditions, resulting from the European cultural influences in park art from the beginning of the 20th century in architecture and urban planning (Sofia, Ruse, Plovdiv, Varna, Burgas). Political decisions in the planning and construction of urban spaces, distinctive for Eastern Europe in the mid and late twentieth century, directly affect the type and condition of green spaces as part of the urban structure. These include representative central city parks, preserved natural tree vegetation in the old parts of the cities and cemetery parks, wide landscaped and mostly grassy expanses in new residential districts, and often isolated suburban green areas which are usually territorially linked to nearby protected natural or cultural sites. The serious political changes of the late twentieth century generated significant changes in the functional specialization of cities, and for some of them led to uncontrolled sprawl (mostly regional cities), greatly complicating their urban structure. Losses of green spaces, changes in their condition, or alterations in their use have been documented.

European policies in the protection and utilization of ecosystem functions through the construction and maintenance of green infrastructure are reflected in Bulgarian political documents [23]. However, the development of a concept for GI in local conditions, and especially a long-term vision for its targeted maintenance and conservation with the motivated cooperation of the public, takes time. The reason for this is primarily rooted in the need to establish an urban planning concept that is adequate to contemporary urban needs and that plans and integrates the functions of green spaces as an integral part of the urban system and a form of infrastructure. However, this is a difficult process whose constraints are rooted in the management conditions on heterogeneous ownership of urban properties, demographic pressures (in the direction of population influx or outflow) stimulating new construction and the expansion of the service sector, or vice versa with issues relating to abandoned buildings and disturbed land. Unfortunately, the fact that the topic of green spaces and their functions is successfully used for political purposes, but the actual construction of green spaces is financed by separate municipal, NGO, or private projects, not always temporally or territorially coordinated, is also relevant here.

For smaller settlements (fewer than 50,000 inhabitants) there is a very general and wishful style of urban policies in managing green spaces. Still, the financial resources are sufficient mainly for the seasonal landscaping of urban gardens in widely publicly accessible urban squares and main pedestrian streets. The Association of Municipalities in Bulgaria has recognized a practical manual for UGI [24], but we will have to see how effective its implementation is in the future.

The main challenge in the implementation of European and national policies (top-down) related to urban greening on a local scale, in our view, is the need to apply an individual approach (bottom-up) in the construction and maintenance of green infrastructure concerning the local geography, the inherent urban structure (settlement development in a historical and geographical context), the demographic profile, and the leading administrative, economic, and cultural functions of the city. However, this depends on the local institutional capacity in solving the current problems of the city, as derivatives of its complexity. On this basis, we assume that a good spatial analysis of the urban morphology and the possibilities for its development given the active variables—population, economy, services, and consumption—enables the construction of green infrastructure, sufficiently flexibly inscribed in the urban structure so that it fulfills its ecological functions to the full. The research of Croeser et al., 2021 [25] draws attention to the potential of multi-criteria decision analysis (MCDA), including the importance of user feedback for the co-creation of knowledge and the selection of adequate solutions to address various urban challenges.

The focus of the present study is a persistent problem for large Bulgarian cities (over 200,000 people): their high vulnerability to dust pollution. This is derived to a high degree from inherited problems of urban structures in the course of their territorial expansion, the change of priority functions under the influence of political changes, demographic variables, and last but not least, geographical conditions. The procedure "Green infrastructure in an urban environment" in the direction "Air" under Operational Program "Environment" 2021–2027 of Bulgaria, financed through the European Structural Funds, supports the greening of urbanized territories, including innovative approaches (NBS). In this regard, municipalities affected by air quality (AQ) problems have the opportunity to receive funding for landscaping investments aimed at reducing secondary dust pollution and improving AQ.

The study presents comprehensive research results in Burgas, the second-largest urban area city in Bulgaria, with leading economic functions in South-Eastern Bulgaria. The main objective of the study is to develop and test a model for geospatial analysis of the urbanized area of Burgas to select locations where the construction of new or the renovation of existing green infrastructure elements can contribute sustainably to the reduction and mitigation of air pollution, and in particular secondary dust pollution. The study is based on the relationship between urban morphology, the green system, and ecosystem services for air quality regulation. The results support Burgas's urban planning and greening concepts.

This has been realized in active cooperation with the Municipality of Burgas: we have approached this with the understanding that the model must be understandable for the managers and able to undergo periodic discussion and optimization as a result of effective feedback from the interested parties. The study was carried out with the following pre-set requirements: (1) the study should interpret the relationship between GI and ESs in the context of Burgas' distinctive urban structural heterogeneity; (2) the study should use local data (information maintained and integrated by the local authority for city management purposes, and potentially updatable through regular monitoring programs); and (3) the results should have a long-term effect on the reduction in PM with successful synergy with other regulating ecosystem services necessary for the city, such as cooling effects, climate comfort, and habitat functions. The desired result is a sustainable provision of ESs for PM reduction in support of the activities laid down in the current "Program for improving the air quality of the municipality of Burgas for 2021–2027" [26].

2. Materials and Methods

Significant epidemiological studies in the scientific literature find that air pollution contributes to increased morbidity [27]. Air pollution, mainly caused by nitrogen dioxide (NO_2) and fine particulate matter with an aerodynamic diameter below 2.5 µm ($PM_{2.5}$), is today the leading environmental cause of death worldwide, causing over 3 million premature deaths per year, more than twice the number of deaths from road traffic accidents [1]. Green areas and their ecological functions contribute to ambient AQ by reducing and removing air pollutants, especially PM. This has been demonstrated in many studies in recent years, and interest in the topic has increased concerning the increased incidence of disease in urban populations in densely built settlements [28–31].

Ground-level concentrations of air pollutants in cities are a complex function of emissions, dispersion, and deposition of pollutants, and chemical processes in the surface air layer. These processes are largely influenced by the geospatial structure of the city. The conceptual framework of this study is based on several key assumptions related to the role of UGI. We assume that UGI will have the most significant impact on AQ by stimulating natural ventilation; changing the mean aerodynamic roughness (which has a direct impact on pollutant dispersion); absorbing pollutants from green surfaces (leaves, branches, tree bark); limiting the formation of secondary pollutants due to cooling effects. Based on these initial positions, the analysis of the UGI elements of the urban area of Burgas is analyzed as an integral structural part of the city morphology.

2.1. Study Area

Burgas City is a functional urbanized area center with major industrial, transport, and tourist functions in South-Eastern Bulgaria. Burgas is located on the coast of Burgas Bay on the southern Black Sea coast (17 m a.s.l.) and experiences a continental Mediterranean climate (Cfa). It is the second largest urbanized area (254 km^2) after the metropolitan city of Sofia, and hosts 4% of the country's urban population [32]. It is distinguished by an over-concentrated urban core developed around a port, with annexed settlements from the agricultural periphery that are now important residential districts. The urban structure is set among three coastal lakes and the Black Sea (the city is surrounded by the largest complex of seaside lakes in the country) [33] (Figure 1). Its territory is distinguished by a concentration of protected areas of national and European importance.

The Environment Executive Agency of Bulgaria defines the city of Burgas as a zone/territorial unit in which atmospheric air pollution with fine dust particles (PM10) exceeds the permissible number of exceedances (up to 35 days/year of the average day and night norms of 50 µg/m^3). For 2016–2020, exceedances of up to 116 days (2017) were registered here, with average values for 74 days/year [34]. Since 2013, the territory has been part of the Autonomous Region for the Assessment and Management of AAQ and is obliged to develop and implement targeted programs to reduce pollutant levels. Within the scope of the analyzed area, there are year-round conditions for the retention of pollutants in the surface air layer: high frequency of maximum temperatures above 30 °C during the summer months; absolute maximum temperatures for the period June–August of up to 40–42 °C;

and high atmospheric humidity but insufficient amount of annual average precipitation (between 470 and 600 mm). Cases with low wind speeds (up to 1.5 m/s) reach 20–24% in the period from March to July, while in the remaining months, they vary between 12–15% (Program for Improvement of Ambient Air Quality in the Municipality of Burgas) [26,35]. The configuration of the city does not allow good ground ventilation, which confirms the strong influence of the city's morphology and its economic activity on microclimatic conditions and AQ.

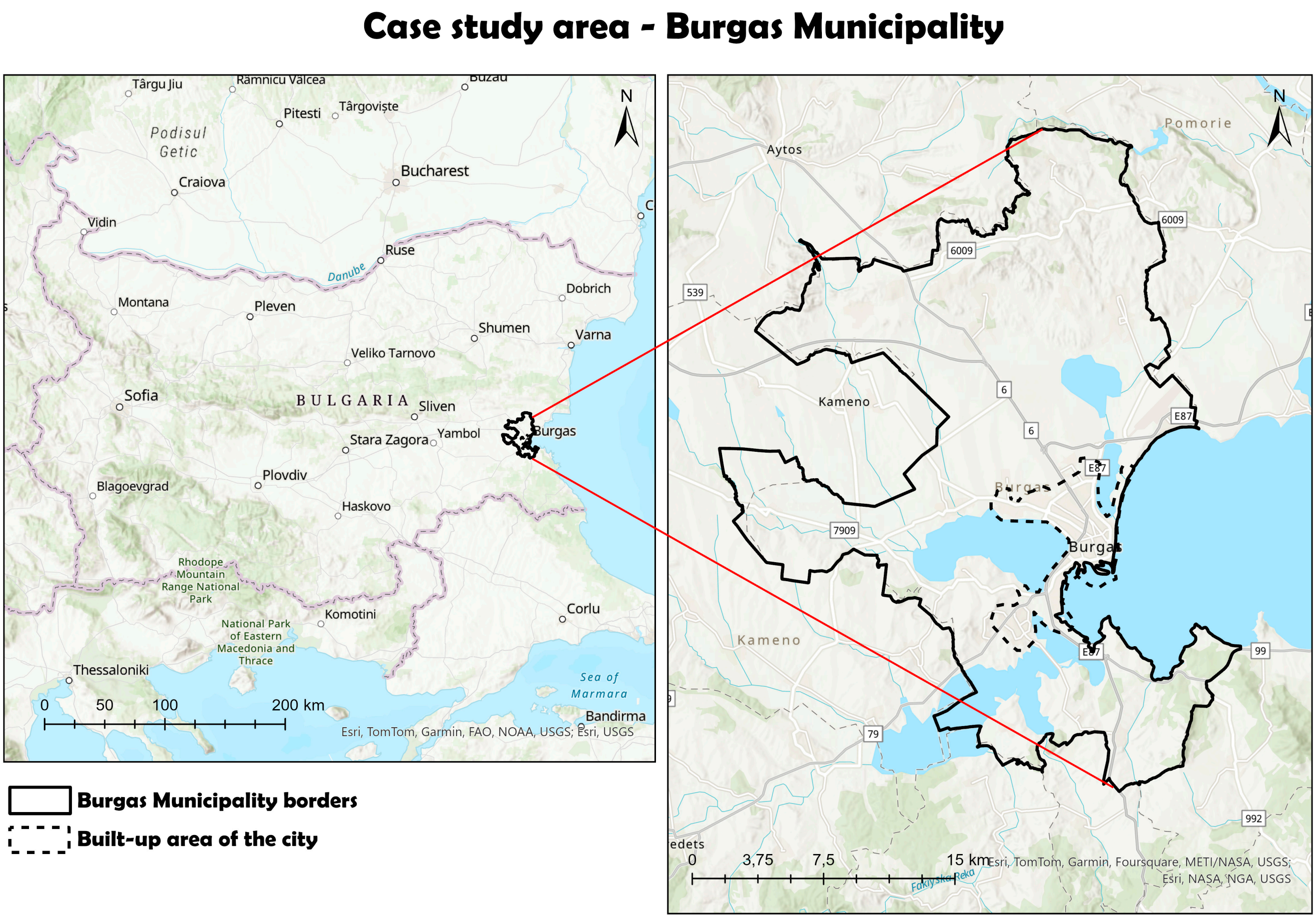

Figure 1. Study area—Burgas city and municipality.

Although the territory of the municipality is characterized by very good coverage of green spaces, the trends listed above make it imperative to consider expanding green spaces in urban environments to increase the cooling effect and aid in the sedimentation and reduction of air pollutants.

2.2. Approaches and Methods for Geospatial Analysis of Urban Environment Related to Air Quality Improvement and Reduction in Secondary Dust Pollution

This study proposes an approach for geospatial locational analysis of the urban morphostructure of the city of Burgas, aimed at a scientifically substantiated selection of sites/objects where the expansion or renovation of green areas can help reduce secondary dust pollution. The methodology integrates 12 indicators reflecting local conditions, including urban heterogeneity, locations with high concentrations of PM, local microclimatic conditions, conditions of the UGI, population, and social activities. The study is consistent with the principles of effectiveness and feasibility.

A methodological framework has been developed assuming the sequential implementation of the following work phases and activities (Figure 2):

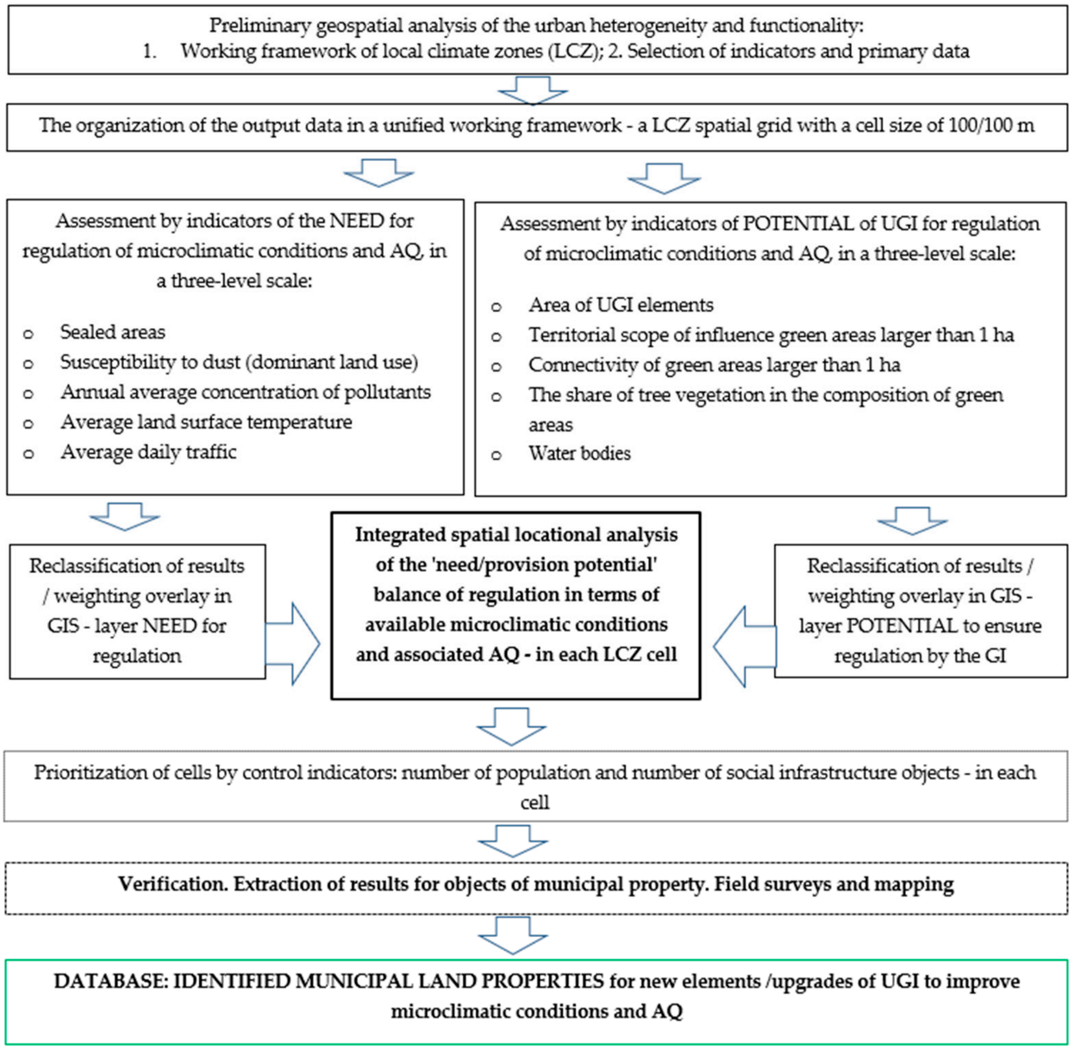

Figure 2. Methodological scheme.

Phase 1: Preliminary geospatial analysis of the urban spaces of Burgas to identify the main features of urban heterogeneity and functionality. This phase aims to define a basic working spatial unit (unified working framework) for carrying out spatial assessments and selecting indicators to reflect the influence of the urban environment on the AQ. For the preparation of a basic spatial unit, this study uses the concept of local climate zones, arguments for which are presented in item 2.3. A cell size of 100 × 100 m (area of 1 ha) is applied.

Phase 2: Unification. This phase includes the organization of the output working data according to the unified working framework defined in Phase 1 and the development of a scale consistent with the framework for measuring the selected indicators for territorial assessment: A three-level scale was chosen to evaluate a total of 12 indicators determined to be informative for the study.

Phase 3: Integrated spatial location analysis. This stage has three steps, as follows: 1. assessment by 5 indicators of the 'need' for regulation of microclimatic conditions and AQ, and assessment by 5 indicators of the 'potential' of UGI to ensure regulation of microclimatic conditions and AQ; 2. weighting overlay in a GIS by thematic grouping of the results of the evaluation of the indicated indicators for each cell of the LCZ; and 3. reclassification of the results and the identification of the 'need/provision potential' ratio for each LCZ cell—the aim being to identify cells in which there is a high need for AQ regulation, but a low available UGI potential.

Phase 4: Prioritization. This phase envisages prioritization of the cells with the most unfavorable 'need/provision potential' balance—a result of the previous phase. For this, the introduction of control indicators is foreseen: number of population and number of social infrastructure objects—for each LCZ cell. A three-level scale was used to rank the values of both control indicators.

Phase 5: Verification and discussion. This phase includes verification of the results through a detailed survey of the prioritized territories according to current photogrammetric data with and field visits; extraction of results for objects of municipal property; discussion of the results with the responsible persons in the municipality and other interested parties; and measurement of the areas within the properties for which greening measures are applicable.

Phase 6: Organization of the received information about the selected terrains/objects in a database: geolocation identifiers, reference to the property cadastre, the purpose of UGI concerning the type of permanent use of the terrain, and other attributive data obtained in the course of the research and thematic assessments.

A series of analytical operations were conducted in a GIS environment using ESRI's ArcGIS Pro software 3.2.0 to sequentially process the data.

2.3. Unified Working Framework for Spatial Assessments—Local Climate Zones

For the integrated locational analysis, this study applies the Climate Classification Methodology for Urban Areas [35], which allows the analysis of key features of the urban space in a system of cells with the meaning of "local climate zones" (LCZs). This decision is based on the following arguments: LCZs reflect urban morphology in specific spatial combinations of built area types and adjacent land cover [35]. Among the most important arguments is the potential of the LCZ to reflect the prerequisites for microclimatic conditions and corresponding AQ in the heterogeneous urban structure against the background of climate regimes common to the urban space of Burgas. In addition, LCZs determine important characteristics of urban climate (temperature regime, including the urban heat island effect (UHI), and surface air circulation), air quality, and dust and pollutant retention conditions [36,37]. LCZs could facilitate the discussion and mapping of spatial PM pollution [38]. LCZs are an effective framework for discussing urban sustainability and climate neutrality. The versatility, simplicity, and objectivity of the LCA framework make it a promising tool for a wide range of applications in the future, especially in the field of climate-smart urban planning and design [39]. LCZs are used as the main information unit in the definition of the typology of urban ecosystems in the Methodology for assessment and mapping of urban ecosystems and urban ecosystem services in Bulgaria [40]. On this basis, green urban infrastructure has been assessed as a provider of regulating Ess in terms of AQ.

The main stages of LCZ definition generally include the following research procedures: (1) grid size selection; (2) zone definition according to the classification scheme (Stewart and Oke, 2012), (3) visualization of the results; and (3) statistical characterization of the respective zones obtained by processing geostatistical data or data from field measurements [41].

2.4. Indicators

As a result of the preliminary analysis, a total of 12 indicators have been identified for participation in the integrated geospatial analysis (10 thematic and 2 control indicators). The selection is in line with the choice of the LCZ as the territorial unit for assessment. The final decision was made after a discussion with the Burgas Municipality regarding the provision of up-to-date data: the study uses data from the Smart Burgas integrated city information platform (https://smartburgas.eu/bg, (accessed on 13 August 2024)) [42], used by the local administration for the management of Burgas City and direct feedback to the residents of the city. These are data from regulatory local monitoring (air quality), including the functioning of urban infrastructure (such as 24 h car traffic); urban planning data (locations of social infrastructure sites), or data generated at the request of the municipality for urban planning purposes (photogrammetric surveys of the actual land cover of the city, including the extent of green areas); and data from open national data of the National Statistical Institute (population). A unified three-level scale has been developed to measure the indicators applied in the study (except for the "water bodies" indicator, where the actual presence of similar urban elements is taken into consideration). Each level of this scale assumes in the course of the assessment a corresponding weighting—high, medium, and low.

Indicators for the air quality assessment/demand to provide air quality regulation.

Five indicators were selected to reflect the relationship between urban heterogeneity and ambient air quality (Table 1). The sealing of natural surfaces in the process of urban development and sprawl with artificial or low permeability materials results in the permanent disruption of natural internal landscape processes such as water and air circulation, soil functions, biological nutrition, and bioproduction. The high concentration of sealing in Burgas and the compact urban structure (with a population density of 746 people/km^2) contribute to the retention of high concentrations of PM in ground air and resuspension of PM. The indicator of susceptibility to dust reflects the leading type of land use in the respective LCZ grid cell. Here, the assumption is made that according to the type of land use and the functioning of the respective territory (residential, industrial, transport, public services, sport and recreation, nature conservation, etc.), a certain susceptibility of urban areas to dusting is formed. The role of the transport arteries of the city in the emission of resuspended dust is reflected in a separate indicator: the average daily intensity of motor vehicles on the main transport arteries in Burgas. In the selection of baseline data, a value of 10,000 vehicles/day was used as a critical threshold.

The indicator for PM pollution reflects aggregated spatial results for annual average concentrations of PM_{10} from all sources and the formation of pollution hotspots in the city of Burgas. The assessment scale is consistent with the World Health Organization's air quality guidelines and its reference levels for the allowable annual mean concentration for $PM_{2.5}$ and PM_{10} [43]. The same source states that $PM_{2.5}$ makes up between 50 and 80% of the weight of PM_{10}. Current data on the concentration of $PM_{2.5}$ in Burgas at the time of this analysis (May–June 2024) show that they are the main pollutant of ambient air in the city of Burgas [44].

The high percentage of sealed surfaces and the configuration of the built-up area create the conditions for the occurrence of higher average surface and ground air temperatures in urban areas. A systematic review of the existing scientific literature on the subject reveals a complex relationship between air pollution and urban heat islands: on the one hand, air pollution contributes to the heating of urban areas, and on the other hand, urban heat island effects influence air quality [45]. The combined effect of these two threats contributes significantly to climate change and its derivative effects in urban settings. The criterion chosen here is the mean land surface temperature measured around noon local time (based on Landsat 8 data from 30 July 2022). The choice of the time range is determined by the direct influence that the land surface temperature (LST) has on the temperature and dynamics of the ground air, and with this on the dispersion of the PM in the vertical air exchange. Comparative analysis with evening temperatures after sunset (based on data from previous observations [36]) gives us reasons to assume that the LST during daylight hours has a much more significant influence on the dusting process. Based on the obtained raster temperature values, an average LST for each LCZ cell was calculated using zonal statistics.

Table 1. Air quality indicators, parameters, scores, and data sources for geospatial analysis.

Indicators and Parameters (Calculated for Each LCZ)		Evaluation Scale	Data Used for the Analysis
1.	Sealed areas (Area in %)	Low: 0–30% Medium: 30–60% High: >60%	Spatial layer of urban green areas (*Geographica Ltd., Sofia, Bulgaria*)
2.	Susceptibility to dust (Type of LCZ according to dominant land use)	Low: LCZ A, B, D, G Medium: LCZ 6, 9, C High: LCZ 3, 4, 5, 8, 10, E	Orthofoto image of Burgas, 2022 (*Geographica Ltd., Sofia, Bulgaria*)
3.	PM_{10} concentrations (Annual mean concentrations, 2019)	Low: <15 $\mu g/m^3$ Medium: 5–15 $\mu g/m^3$ High: >15 $\mu g/m^3$	Municipality air quality report [46]
4.	Average land surface temperature (°C)	Low: Up to 24 °C Medium: Up to 28 °C High: Over 28 °C	Landsat 8 Satellite image [47]
5.	Traffic (Average daily traffic—number of vehicles/24 h)	Low: Up to 10,000 Medium: 10,001–25,000 High: Over 25,001	Numbers of daily traffic (*Burgas Municipality, Burgas, Bulgaria*)

Indicators for assessing green infrastructure/potential for providing regulation of air quality and reducing secondary pollution.

To reflect the role of GI on ambient air quality through the reduction in PM, a combination of indicators has been selected, appropriate to the nature of the available data and the scale of the study (Table 2). For this purpose, baseline data from the green system of the city of Burgas (https://greensystem.smartburgas.eu/, accessed on 13 August 2024) [48] were used. Important spatial factors such as the overall provision of natural environmental elements (inherited and new) and projective cover—green elements and water bodies—are taken into account. An indicator is introduced to reflect the spatial extent of the influence of green elements on their contact environment. This has been implemented by analyzing an average distance of 50 m from green areas over 1 ha. The connectivity factor increases the effectiveness of green elements in the regulation of microclimatic conditions and the improvement of the AQ. Here, the indicator takes into account the connectivity of urban parks and green areas with a spatial extent of more than 2 ha.

Urban tree vegetation has a leading role in reducing PM compared to other types of urban vegetation, which is explained by plant morphology [49]. For the conditions of the city of Burgas, the cooling effect provided by the GI is additionally important, as it mediates the reduction in PM by favoring microclimatic conditions. The indicator used here represents the area distribution (%) of the tree canopy for each LCZ grid cell. Cells with no tree cover are scored as '0'. The assessment of the indicator was carried out in several sequential steps: initial selection of tree vegetation over 3 m in height; selection of cells with an average tree vegetation height below 5 m and creation of a 25 m^2 buffer for each tree falling within these LCZs. Selection of cells with an average height of tree vegetation above 10 m and the creation of a buffer of 40 m^2 for each tree falling within these LCZs.

The study also applied additional indicators involved in the final prioritization of sites for investment in the GI (Table 3). This was implemented by introducing in the assessment (per each LCZ grid cell) information on the spatial concentration of social infrastructure facilities (health facilities, social institutions, educational facilities, kindergartens, universities, sports facilities, and playgrounds) and population number.

Table 2. UGI indicators, parameters, scores, and data sources for geospatial analysis.

Indicators and Parameters (Calculated for Each LCZ)	Evaluation Scale	Data Used for the Analysis
1. Green areas (area in %)	Low: 0–30% Medium: 30–60% High: <60%	Spatial layer of urban green areas (*Geographica Ltd.*, *Sofia*, *Bulgaria*)
2. Impact of green areas larger than 1 ha (meters)	Low: Over 300 m Medium: Up to 300 m High: Up to 100 m	
3. Connectivity of green areas larger than 1 ha (100 m distance between individual green patches)	Low: No connectivity Medium: 50–90% High: 100%	Spatial layer of urban green areas (*Geographica Ltd.*, *Sofia*, *Bulgaria*)
4. Contribution of tree vegetation to the composition of existing green areas (% canopy cover)	Low: Up to 25% Medium: Up to 50% High: over 50%	Spatial layer of urban trees/point feature/(*Geographica Ltd.*, *Sofia*, *Bulgaria*)
5. Water (presence of water bodies)	Low: No High: Yes	Orthofoto image of Burgas, 2022 (*Geographica Ltd.*, *Sofia*, *Bulgaria*)

Table 3. Prioritization indicators, parameters, scores, and data sources for geospatial analysis.

Indicators and Parameters (Calculated for Each LCZ)	Evaluation Scale	Data Used for the Analysis
1. Spatial concentration of public facilities (Number)	Low: No facilities Medium: 1–2 High: 3–4	Spatial layer of public facilities/point features(*Burgas Municipality*, *Burgas*, *Bulgaria*)
2. Population (Number)	Low: Up to 100 Medium: Up to 200 High: Over 200	Number of population by neighborhood (*Burgas Municipality*, *Burgas*, *Bulgaria*)

3. Results

3.1. Local Climate Zones

Within the urban area of Burgas City, 14 types of LCZ have been identified (Table 4, Figure 3). They are organized in territorial units of the same size and shape—a uniform grid with sides 100 m × 100 m with an area of 1 ha, which gives enough area for a site to be defined as a specific LCZ. Smaller cell sizes imply a risk that separated LCZs could be wrongly defined based on the absence of a particular element. They number 3789 in total. The LCZs were determined based on highly detailed digital models of the study area (2022). Based on these models, parameters such as density of development, percentage coverage of sealed areas, or presence of vegetation have been accurately extracted. After the LCZ classification, a field verification was performed.

Table 4. Local climate zones in Burgas.

LCZ	Number of Cells in Total	Area in %
LCZ_3 Compact low-rise buildings	28	1
LCZ_4 Open high-rise buildings	49	1
LCZ_5 Open midrise buildings	814	21
LCZ_6 Open low-rise buildings	180	5

Table 4. *Cont.*

LCZ	Number of Cells in Total	Area in %
LCZ_8 Large low-rise buildings	882	23
LCZ_9 Sparsely built	122	3
LCZ_10 Heavy industry	50	1
LCZ_A Dense trees	21	1
LCZ_B Scattered trees	246	6
LCZ_C Bush, scrub	69	2
LCZ_D Low plants	491	13
LCZ_E Bare rock or paved	196	5
LCZ_F Bare soil or sand	59	2
LCZ_G Water	582	15
Total	**3789**	**100**

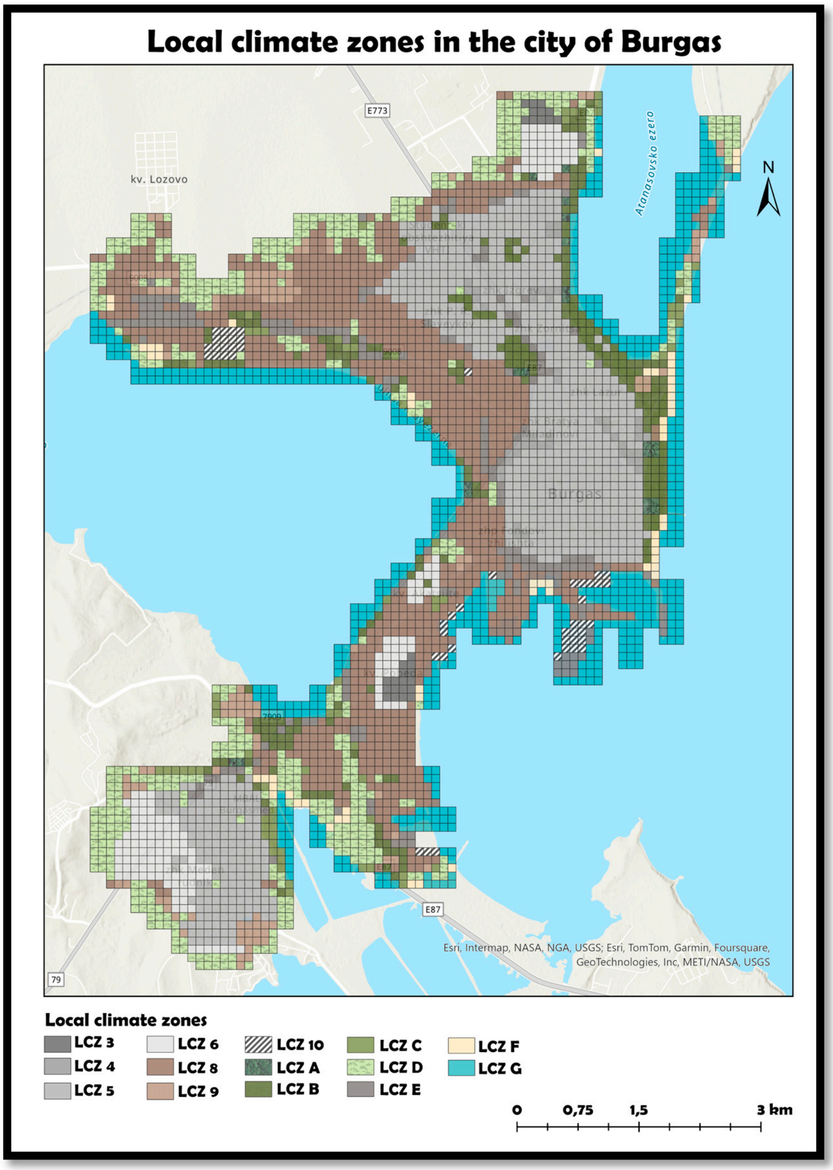

Figure 3. Local climate zones in the city of Burgas.

As shown in Table 4, according to the type of construction, the largest area is occupied by open midrise buildings (residential neighborhoods) and large low-rise buildings (industrial buildings).

3.2. Integrated Geospatial Analysis of the Balance "Air Quality Regulation Demand and Potential to Reduce Secondary Dust Pollution from the Urban Green Infrastructure" and Prioritization of Cells through Control Indicators

The spatial results of the thematic assessment of the indicators concerning the unfavorable preconditions and existing circumstances for the deterioration of the AQ are presented in Figure 4. The result is considered as degrees (low, medium, and high) of "demand to introduce measures to mitigate secondary spraying" (Figure 5). The aggregated results show a high vulnerability to dust pollution in the over-concentrated urban core and along major transport links. This is a complex result of the urban structure of Burgas in these ecological and geographical conditions and its modern functional specialization. However, with the greatest influence on the concentration of demand for air quality regulation in the central urban area are the high percentage of sealed surfaces (over 60%), the high values of pollution with PM (over 15 μg/m^3), and the concentration on busy boulevards.

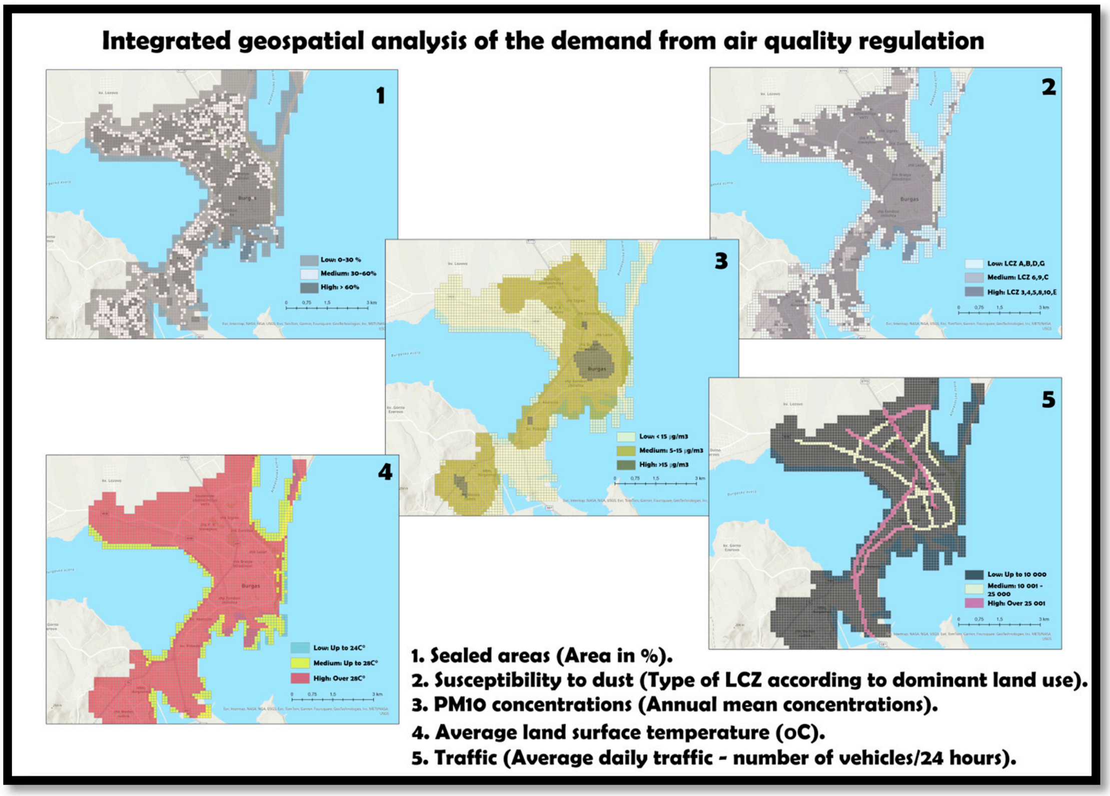

Figure 4. Integrated geospatial analysis of the demand from air quality regulation—overlay analysis.

The spatial results of the implemented indicators for the assessment of UGI, i.e., the potential to provide air quality regulation and secondary dust pollution reduction, are presented in Figure 6. The summarized results give a reason to point out that in general there is a favorable overall structure of the green system of the urban space in the city of Burgas. This is particularly evident in the northeastern parts of the city as well as on the periphery. This high potential is mainly because, in the above-mentioned areas, the percentage of greenery in the grid is high (over 60%), supported by the positive values of the other important functions of UGI: the impact and connectivity of green areas, and last but not least, the presence of water bodies (Figure 7).

The outcome of this phase of the study is the identification of grid cells/LCZs with high and medium values of "demand for air quality regulation" but with low "potential for air quality regulation"—cells that are deficient in regulatory mechanisms to mitigate secondary sputtering and need to upgrade/rebuild air quality elements. The results of the integrated analysis found that in the central areas of the city of Burgas, there are compact areas along the main boulevards where it is necessary to implement measures to mitigate secondary dust pollution through the construction of elements of the UGI. These results have been used as the basis for the subsequent steps of prioritization of the areas and spatial definition of the sites/territories for targeted intervention to build the elements of the UGI (Figure 8).

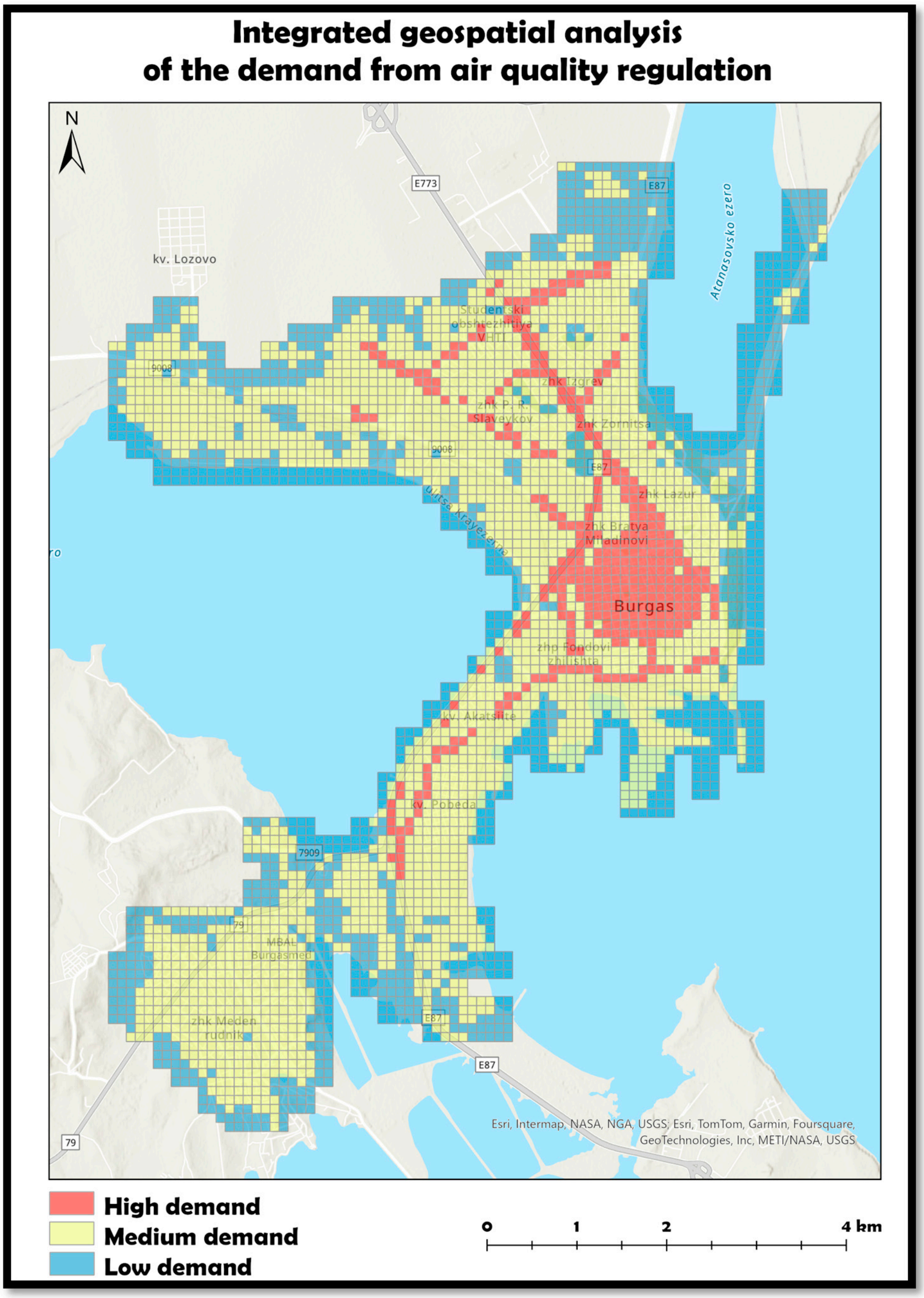

Figure 5. Integrated geospatial analysis of the demand from air quality regulation.

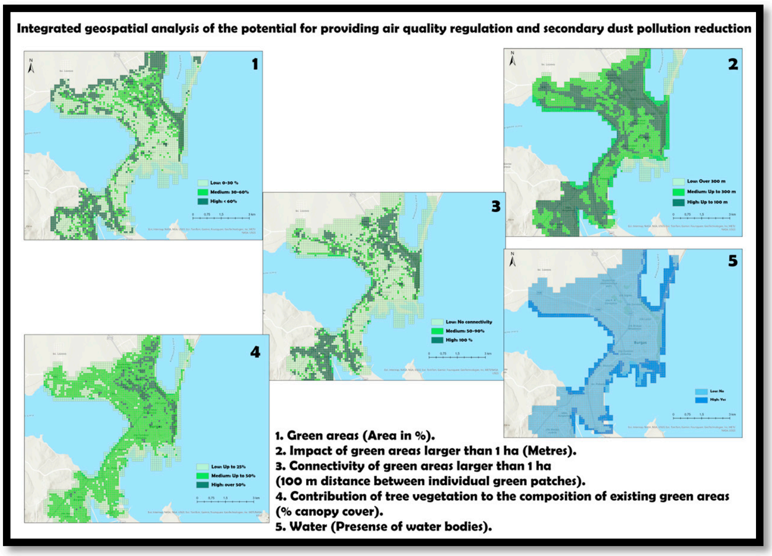

Figure 6. Integrated geospatial analysis of the potential for providing air quality regulation and secondary dust pollution reduction—overlay analysis.

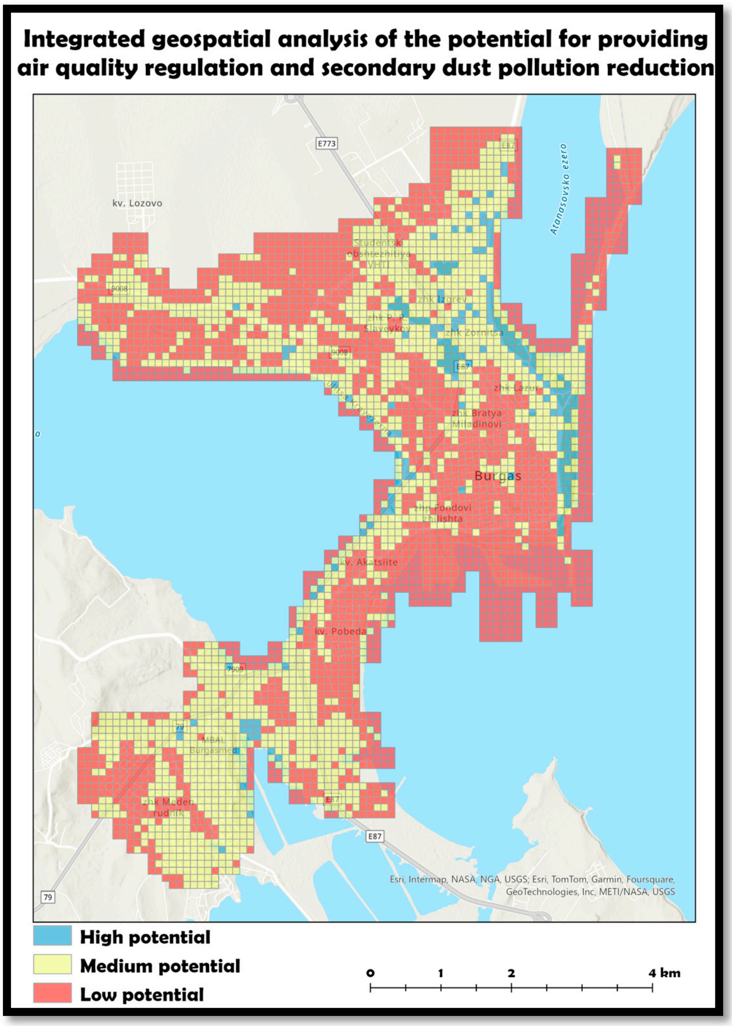

Figure 7. Integrated geospatial analysis of the potential for providing air quality regulation and secondary dust pollution reduction.

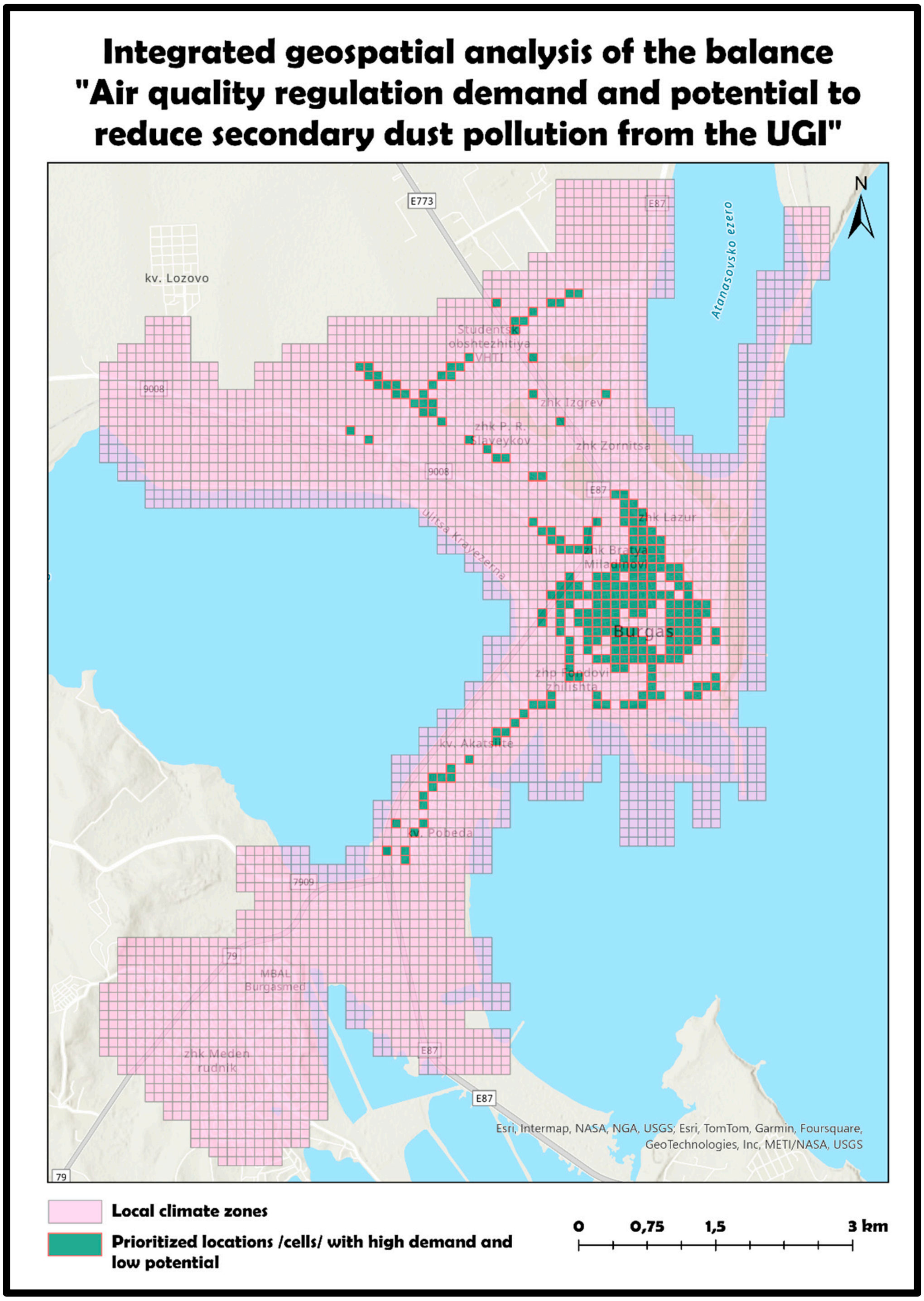

Figure 8. Integrated geospatial analysis of the balance "Air quality regulation demand and potential to reduce secondary dust pollution from the UGI".

The data obtained from the assessment of the "demand/potential" balance are subjected to secondary analysis by introducing information on the presence and spatial concentration of public social facilities and population. A total of 79 cells of priority importance for landscaping have been identified. Their total area is 0.79 km^2.

3.3. Selection of Urban Green Infrastructure Investment Locations

As a result of the complex geolocalization analysis, two groups of priority spatial locations (a total of 79 grid cells/LCZs) have been identified for investment and construction of components of the UGI.

1. Group 1 (47 LCZs)—highest priority locations: a high concentration of social facilities (three to four sites), with a population density of over 200 people per cell (relevant LCZ), with a 'high' need for the introduction of secondary dust mitigation measures, but a 'low' potential of provision from the available UGI structure.
2. Group 2 (32 LCZs)—high priority locations: a high concentration of social facilities (three to four sites), with a population density of over 200 people per cell (relevant LCZ), with a 'medium' need for the introduction of secondary dust mitigation measures, but a 'low' potential of provision from the available UGI structure (Figure 9).

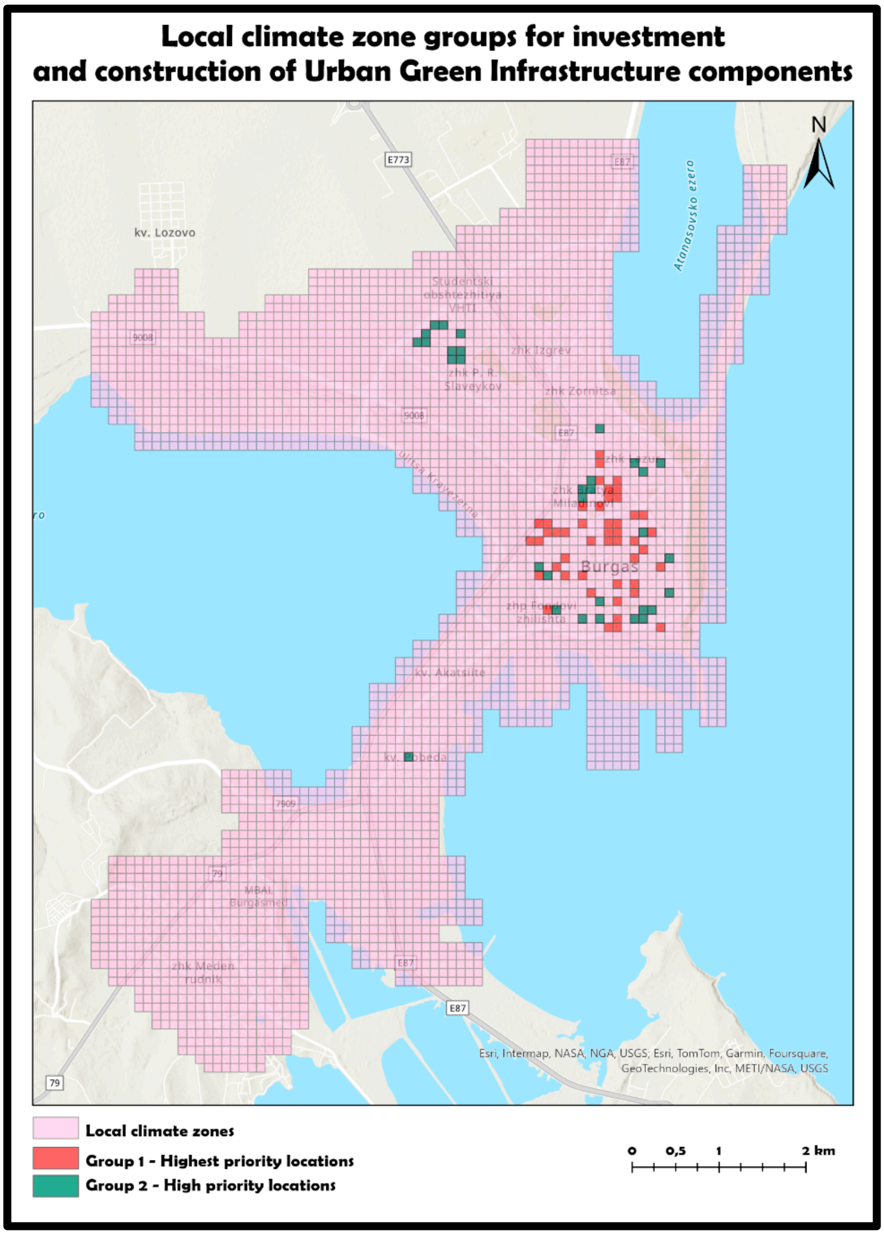

Figure 9. Local climate zone groups for investment and construction of UGI components.

A spatial analysis of potential green areas in the city of Burgas revealed that 112 identified sites are located within a 100 m radius of social facilities. Among these, 17 sites are situated within municipal educational centers, such as schools and kindergartens. Another 41 properties designated for greening fall within 100 m of educational institutions across the city. Furthermore, 75 playgrounds benefit from this proximity to the identified green areas. Within the 100 m buffer surrounding eight of the identified green spaces, there are five or more social infrastructure objects, with the highest concentration being eight near an identified area along Yanko Komitov Boulevard. This clustering of green spaces near multiple social infrastructure elements, especially near schools, kindergartens, and playgrounds, highlights their strategic importance in urban planning, offering opportunities to enhance accessibility to green areas.

Based on the above-mentioned prioritized LCZs, in close proximity to/around, 174 properties (municipal ownership only) have been identified for future planned investments in UGI. The total area of the identified areas for landscaping in the mentioned properties is 15 ha. The results were discussed with the responsible parties from the Municipality of Burgas—emphasis was placed on the disturbed areas identified in the course of the field verification (bare surfaces without vegetation or disturbed pavements—a permanent source of dust pollution). Feedback was sought from the Landscaping Directorate regarding the qualitative characterization of the green elements and the health of the vegetation in the prioritized cells. It is recommended to study the results of targeted research [50] for the selection of species for afforestation that are drought-tolerant and disease-resistant in the climatic conditions of Southeastern Bulgaria.

Spatial data for the identified landscaping locations, along with detailed attributive information, has been provided to the Burgas Municipality in convenient file formats. Some of the attributive information includes the following data: identifier, cadastral number, and ownership of the property according to the National Property Register; area of the property by cadastral map; and the area of identified landscaping areas. Information on the locations/investment areas on which a new UGI will be built or constructed to address secondary dust pollution mitigation is organized as follows (Figure 10):

- For roadside landscaping along busy urban streets/boulevards (outside the national road network).
- For spaces between blocks—public spaces with open access (publicly accessible), including city parks, gardens, squares, and spaces between city blocks that have a disturbed structure (mud patches).
- For social infrastructure facilities—outdoor school areas and those on the territory of kindergartens—municipal property.

Evidence has been collected in geolocation images which have been added to the other attribute information. In the preparation phase of the landscaping projects, the team of this study, together with the urban planners of the Burgas Municipality, will discuss the possibilities of applying innovative NBS to contribute to a reduction in secondary dust.

To extract the maximum amount of practical information to support discussions for future projects, some of the locations identified with the highest demand for investment in the construction of GI were mapped with the laser scan system GEOSLAM ZEB Horizon (Figure 11).

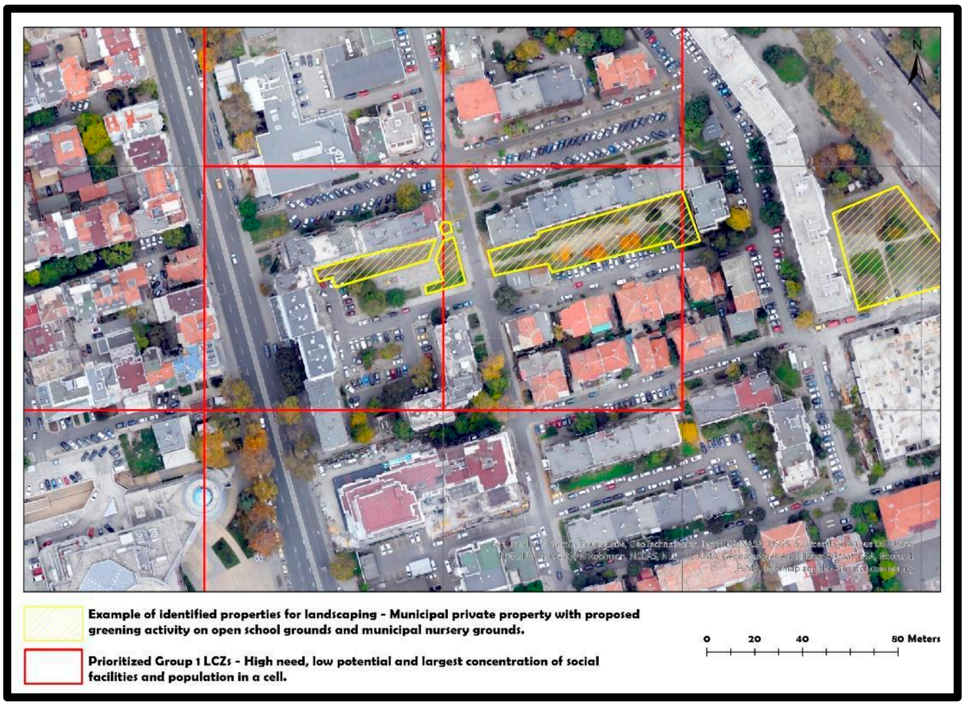

Figure 10. Example with identified properties for landscaping.

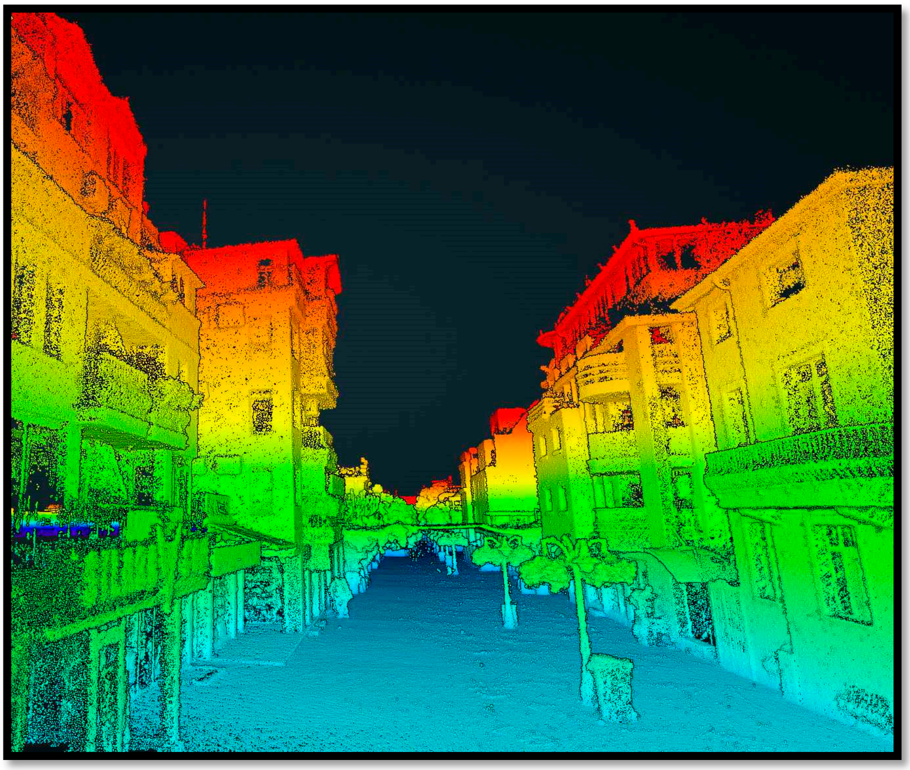

Figure 11. Locations mapped with laser scan system GEOSLAM ZEB Horizon.

4. Discussion

The assumption that GI can improve air quality is widely held in the public health [29], urban planning [51], and ES literature [52]. The UN's Environmental-Economic Accounting offers vegetation as an environmentally friendly solution to reduce air pollution [53]. The main mechanisms by which air pollution can be reduced by vegetation include deposition and dispersion. However, depending on vegetation structure (plant height, leaf density), site context (e.g., street canyon geometry, distance to emission source), and prevailing meteorological conditions (such as wind speed and direction), the effects of ventilation and dispersion may be thwarted [54]. This is a serious challenge in the design of park spaces [10,55].

The effectiveness of UGI in reducing dust pollution can be a controversial topic and draws attention to the role of urban microclimate on environmental quality. However, urban climate data are tracked from a limited number of monitoring sites and present a general picture with a range of variability in the values of urban climate elements. Such information is unrecognizable by urban planners and landscape architects and is difficult to incorporate into the planning of specific urban spaces, especially in response to local urban challenges. Local microclimatic research requires significant financial and time resources. It is justified when they are conducted for the planning of specialized NBS adapted to a problem location, or in a private project when the site is of great public importance. However, in developing a unified framework for city landscaping and discussing its financing, they are inapplicable.

Our response to this challenge is to conduct research that directly links green infrastructure to local climate zoning. This approach provides a scientific basis for correctly capturing the causal relationship between urban structures, microclimate, and the ecological environment. The approach offers information for taking actions whereby influencing elements of the urban fabric (greening in specific properties in terms of area and configuration) influences microclimatic conditions and AQ.

In essence, our approach creates an information basis for building a unified city-wide approach to planning and implementing landscaping interventions in a form that is understandable to all parties involved in the process (managers, administration, urban planners, landscapers, and designers). However, all of this depends on one precondition—precision in defining the LCZ as the basic urban information unit to reflect urban heterogeneity (cover types and urban geometry) and its corresponding environmental quality. Specific arguments in this direction are outlined below.

4.1. The Local Climate Zones and Regulating Ecosystem Services

If urban structure and surface heterogeneity are major determinants of pollutant retention and secondary dust generation, then microclimatic conditions (in an environment of high urban heterogeneity) are significant mediating factors of influence on AQ as a general outcome. The use of LCZ as a unifying framework for tracking spatial and functional relationships between urban structures, microclimate, and AQ, in our view, brings numerous advantages in research informing the development of citywide strategies and action plans. We have approached this research with the understanding that LCZ can provide us with the much-needed causal link between urban structure and ESs that Marques, 2022 [14] draws attention to.

Among the important advantages is the possibility of comparability between areas within the city, as well as an in-depth analysis of a given location in the context of the characteristics of its contact areas and against the background of the functioning of the urban structure as a whole. This approach also provides an opportunity to include in the analyses information concerning local climatic features (in our case through land surface temperature) which regular urban climate monitoring cannot provide, given the limited coverage of the network and the different focus of the observations. LCZs can also facilitate discussion of urban climate change in the context of global climate change. The exclusion of direct data from local climate observations is one of the main drawbacks of the methodology proposed here.

The inconvenience, in this case, is due to the fact that all urban planning activities in Bulgaria are tailored to urban units established for each respective city, which are of different sizes and purposes. However, the LCZ approach offers a good typology option that is understandable for urban planners and landscape designers and brings the obvious advantages of a possible change of scale of the study (when changing the dimensionality of the cells). The approach also implies the identification of cells with a higher contribution to the provision of regulating ESs—this is a good information base that can be combined with further analyses of vegetation structure types and ratios to built-up area types for the optimal provision of regulation. This must take into account the potential environmental "contribution" that the species will be able to make concerning maintenance costs according to the principle of "the right plant in the right place and with the right management" [28].

However, the dimensionality of the LCZ cells mentioned here is fundamental to the precision of the geolocalization analysis. The correct conduct of thematic assessments depends to a large extent on the provision and representativeness of source data at the spatial extent of the basic unit of information thus defined. Therefore, the verification stage plays an important role in eliminating possible errors. This requires high-precision photogrammetric information and a longer period of field observations. The high heterogeneity of the city of Burgas forced a reduction in the cell size to 100 × 100 m to enter the highest possible detail for surface features.

In the course of processing the data provided, several deficiencies were identified that impacted the analysis. Some of the properties fall outside the boundaries of designated LCZs, which has led to their exclusion. In addition, some of the identified areas overlap with areas that are not municipally owned, limiting their ability to be used within the project. The spatial limitation of the grid cells resulted in instances where identified properties fell only partially within their scope, limiting the accuracy of the analysis. These factors highlight the need for additional data verification and correction to ensure greater accuracy and reliability of the analysis.

4.2. Demand and Provision of ESs—Selection of Indicators

Our research adopts the concept of Larondelle et al., 2016 [56] for a transferable methodology for informed planning processes. Our study reveals spatial mismatches in the need for and supply of regulating ESs from the GI. This approach is well suited for discussing urban transformations with stakeholders and the local public and forms a clearer understanding of ESs from the GI. Last but not least, the results of this approach reinforce the role of GI in ensuring the quality of life and the key need (for Bulgarian cities) for green elements to be planned and managed as 'infrastructure'.

However, the specificity we are looking for—the size of areas, locations in the urban structure, and lasting cause-effect relationships for the AQ in that locality—is dependent on a proper selection of indicators to reflect urban conditions and sustainable sources of information. The selection of indicators in the geospatial analysis here is tailored to the capacity of urban governance to provide available data, to update the information, and to periodically assess (the LCZ approach further facilitates this) important spatial dependencies, functional causal relationships, and deficits in the mix of grey and green infrastructure. This flexibility of the methodology is much needed given the high propensity to change urban heterogeneity. In a subsequent extension of the study, we find it appropriate to incorporate information on wind direction and speed, building height and building orientation relative to wind direction, internal structural features of vegetation cover, and seasonal changes in vegetation cover.

4.3. Landscaping of Urban Properties—General or Individual Approach

In considering a unified approach to urban greening, the issue of urban land ownership and the coordination of the allocation of green space in private and public spaces is essential. The city's authority for UGI interventions is limited to municipally owned land. Nevertheless, the database we developed is comprehensive and the city authority could use it to communicate with the landowners. Local government communication with stakeholders and private parties is important and can provide the necessary consistency in the characteristics of adjacent properties to achieve the desired heterogeneity, connectivity, and overall coverage providing UGI regulation of the AQ.

5. Conclusions

This study uses the urban local climate zones as a unified framework for geolocation analysis of Burgas City, selecting sites where UGI interventions can address public needs for AQ regulation and secondary dust reduction. In six methodological steps, with public information and in direct consultations with municipal management, 174 municipally owned sites suitable for UGI intervention were assessed, prioritized, and mapped. The Burgas Municipality has implemented the results in ongoing landscaping measures in support of the Burgas Municipality's AQ Improvement Program. The results provide a good basis for communication with the municipal leadership, private landowners, and business entities for cooperation in expanding the connectivity and effectiveness of UGI to permanently improve AQ.

The proposed methodological approach has a promising potential for discussing local urban challenges in maintaining a people-friendly living environment. The results are understandable for a wide range of stakeholders and actors and applicable for immediate integration into sustainable urban planning activities.

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