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GIS and geodata contribution to the cartographic modelling of blue-green infrastructure in urbanised areas

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Abstract: The development of cities and peri-urban areas is exerting an increasingly strong impact on the natural environment and, at the same time, on the living conditions and health of people. Problems and challenges that need to be addressed include increasing air pollution in these areas, formation of a surface urban heat island (SUHI), water management disruptions (water scarcity or excess), and the destruction of natural habitats. One of the solutions that contributes to climate change mitigation is the introduction of blue-green infrastructure into the city space and urbanised areas. The research objective was to identify spatial features (geodata) that determine the optimum location of selected blue-green infrastructure (BGI) components, acquire them, and then use the Geographical Information System (GIS) to determine their optimum locations. As the first step, cartographic models were developed which indicated areas that enable the development of selected blue-green infrastructure components in the Olsztyn city area, Warmińsko-Mazurskie Province, Poland. The models were juxtaposed with other two models developed by the authors, i.e. a surface urban heat island model and a demographic model that showed the age structure of the city's population. Consequently, maps with potential locations for the blue-green infrastructure were developed, while taking into account reference data from the National Land Surveying and Cartographic Resource and Landsat 8 images.

Keywords: blue-green infrastructure, drainage system, GIS, Landsat 8 images, map, reference databases, retention, spatial analysis

INTRODUCTION

The level and significance of climate change, as well as the development of cities and peri-urban areas, give rise to the need to seek solutions aimed at mitigating this situation and, grim where possible, reducing the adverse human intervention impact on the natural environment and on people (Zalewski *et al.*, 2012; Bartesaghi Koc, Osmond and Peters, 2017; Cieślak *et al.*, 2019; Antoszewski, Świerk and Krzyżaniak, 2020; Almaaitah *et al.*, 2021; Badach *et al.*, 2022; Siehr, Sun and Aranda Nucamendi, 2022). Many blue-green areas become built up while maintaining a minimum of greenery whose type and surface area mainly resulted from the existing spatial planning regulations. In practice, it often appears that the places which were originally supposed to be designated as green spaces in planning documents also change due to improper use, e.g. as car parks or waiting shelters. However, a positive trend can also increasingly be observed in the application of the assumptions of blue-green infrastructure, particularly in cities (Bowler *et al.*, 2010; Krauze, Wagner and Zalewski, 2014; Drosou *et al.*, 2019; Pluto-Kossakowska, Władyka and Tulkowska, 2020; O'Donnell *et al.*, 2021). Currently, the most reliable type of data on the condition of land is geospatial data. Studies concerning the blue-green infrastructure provide examples of spatial analysis using GIS tools (Zhou and Wu, 2020). This technology allows spatial datasets to be properly acquired, stored and managed and also enables the processing and analysing of these data in order to obtain new reliable spatial information, i.e. information that has a precisely assigned spatial location. Some of the studies in this field have aimed at using the GIS environment to identify the already existing blue-green infrastructure (BGI) (Dennis *et al.*, 2018; Buldakova, 2022) as well as to examine whether existing BGI is sufficient to ensure the inhabitants' quality of life and compliance with legislation (Pluto-Kossakowska, Władyka and Tulkowska, 2020; Mikkili, Panda and Agarwal, 2021). The authors of the aforementioned publications demonstrated the high utility of Geographical Information System (GIS) tools for extracting blue-green infrastructure components and indicating where more BGI should be developed to ensure sustainability. Valuable research is also carried out into the use of remote sensing data to assess the dynamics of changes in land coverage, particularly in the context of rapid and intensive urbanisation (Donati *et al.*, 2022; Thekkan *et al.*, 2022; Gobatti *et al.*, 2023). However, all these studies have a single common denominator, i.e. the automation of the analyses performed and the possibility of carrying them out over an arbitrarily large area, which is also what the authors of this study intend to achieve. It should also be noted that GIS analyses are an excellent tool for seeking, creating, and applying modern solutions that improve an urban environment in response to the rapid and often aggressive urbanisation of space.

The form and the state of spatial development in urban and urbanised areas have evolved over the years. It is quite easy to plan BGI components in vacant and naturally rich spaces, but in areas already occupied, it is hardly possible. One of the scientific articles reviewing information on BGI provides information on the need to identify spatial feasibility of BGI as well as the need to identify effects BGI may have in highly important recreation and tourism areas (Ghofrani, Sposito and Faggian, 2017). The authors of this study decided to investigate the possibilities of analysing and modelling spatial data and GIS data in order to identify possible implementation of selected two forms of BGI and to consequently develop a map of BGI location potential in an urbanised area with recreation and tourism as leading functions.

The main purpose of the study was to develop a map of the location potential of two selected forms of blue-green infrastructure in the area selected. Our research approach uses geospatial data, GIS tools, and remote sensing data to analyse and model spatial information regarding BGI potential. At the same time, the research allowed to verify applicability of individual spatial datasets to optimise location of specific BGI components. The developed set of features should then enable to adapt multi-criteria analysis methods, such as the analytic hierarchy process (AHP) to facilitate a more efficient implementation of BGI in urbanised areas.

MATERIALS AND METHODS

SELECTED COMPONENTS OF BLUE-GREEN INFRASTRUCTURE

The implementation of blue-green infrastructure elements in urbanised areas has been proposed as an approach to mitigate effects of rising temperatures triggered by climate change on human health (Chang, Li and Chang, 2007; Bowler *et al.*, 2010; Lee and Maheswaran, 2011; Völker *et al.*, 2013; Ampatzidis and Kershaw, 2020). Referring to the extensive research confirming the positive impact of blue-green infrastructure, the study focused on elements combining both water and green space elements, namely water retention ponds and bioretention basins.

Blue-green infrastructure (BGI) comprises design of spatial solutions based on the natural potential of a particular site. It is referred to as nature-based solutions (NBS) (Iwaszuk *et al.*, 2019). BGI components should form an integrated system in which services and spatial arrangements complement each other (Zhou and Wu, 2020). In urban areas, BGI can perform multiple functions at the same time. BGI can store and purify water while improving the aesthetic value of a place (Thomas and Bromley, 2000) and, additionally, absorb carbon dioxide, reduce air pollution, or mitigate the urban heat island effect, i.e., control the air temperature. What is more, these components provide habitats for plants and wildlife in urban areas and maintain ecological continuity which also contributes to their environment education function. When properly designed, BGI components reduce excessive surface runoff as well as the risk of flooding (Hamel and Tan, 2022). BGI also contributes to the improvement of mental health and has a positive effect on the well-being of city dwellers, as it offsets adverse effects of climate change through the provision of integrated ecosystem services (Andreucci, Russo and Olszewska-Guizzo, 2019).

All studies concerning design and spatial solutions in the implementation of BGI serve to support planners and architects, including landscape architects, who wish to apply nature-based solutions in cities of all sizes instead of or in addition to traditional infrastructure.

The key services of these ecosystems, offering climate change mitigation and adaptation, include, in particular (Iwaszuk *et al.*, 2019) cooling and insulation, CO_2 absorption, use of low-carbon materials, and the promotion and implementation of sustainable development goals (SDG). Moreover, the distribution of these components should improve the continuity of natural areas, thus promoting their ecological role and significantly increasing biodiversity in the urban environment (Kimic and Ostrysz, 2021).

Below, the authors described selected BGI components that can be optimally used in urbanised areas. Table 1 describes the definition and structure, and distinguishes spatial features that favour location and information about indicated locations for the use of particular BGI components. At the same time, the authors made an attempt to establish a collection of spatial features (geodata) which are fundamental in further analyses of optimal locations for these components (Iwaszuk *et al.*, 2019).

In the scope of this study, the authors analysed spatial features that have been recognised in the cited publications as crucial for selecting optimal locations for BGI elements (Wilson *et al.*, 2009; Eadie, 2011; Avery, 2012; NWRM, 2014; Feit, 2018; Iwaszuk *et al.*, 2019).

Concerning individual features, the analysis revealed that accessibility and quality of publicly available spatial datasets varied. This enabled to select parameters from the table above, which could help to establish a composite indicator to determine the optimal location for individual BGI components. It is worth noting that, the authors decided to rely particularly on public registers of high quality, timeliness, and standardisation. Therefore, the features utilised in spatial analyses facilitated precise location identification, and, more significantly, the reproducibility of analyses in subsequent years.

SPATIAL DATA, THEIR SOURCES, AND THE ANALYSIS OF OPTIMUM BGI LOCATIONS

The information provided in Table 1 on the spatial features conducive to the location of these components helped to move to the geoinformation analysis. A relevant diagram is included in Figure 1.

For the purpose of the analyses, the data are divided into three groups (Fig. 1). The first group (group A) comprises data which exclude the optimum location of BGI components. According to the analysed data sets, this class in the analysis comprises surface waters, buildings, and roads. The location of these spatial components as a whole (AEBGI – areas excluding blue-green infrastructure) is shown in the map in Figure 2. Considering data accuracy and timeliness, these data are extracted from the topographic reference database BDOT10k resource (GUGiK, 2023).

The second group (group B) comprised data from which information on the optimum location of selected BGI components can be extracted. These are listed in Table 1 and subject to a detailed analysis in chapter "Selected components of blue-green infrastructure" (Iwaszuk *et al.*, 2019).

Table 1. Blue-green infrastructure (BGI) components selected for analysis – general information, structure, and geospatial features that generate the optimum location

BGI components	Definition and structure	Spatial features conducive to the location
		place of application
1. Water retention pond	A pond or a basin permanently filled with water, with additional retention capacity to retain and purify rainwater	– land depression; – no contact with the already existing natural water bodies; – minimum area to be drained: 3–10 ha; – pond size at an average depth of 1 m: 3–7% of the overall drainage basin area
		public spaces – parks, city squares
2. Bioretention basin	Comprises areas densely covered with vegetation; rainwater gathers on them and is purified by percolating through successive layers of substrate; this water soaks into the ground or is discharged into the storm drainage system or other receptors; bioretention basins can be designed on a small scale	– area: at least 5% of the overall drainage basin area; – the maximum area should not exceed 2 ha, optimally up to 1 ha
		– heavily urbanised areas (e.g., residential communities and car parks); – firmly sealed surfaces

Source: own elaboration acc. to Wilson *et al.* (2009), Eadie (2011), Avery (2012), NWRM (2014), Feit (2018), Iwaszuk *et al.* (2019).

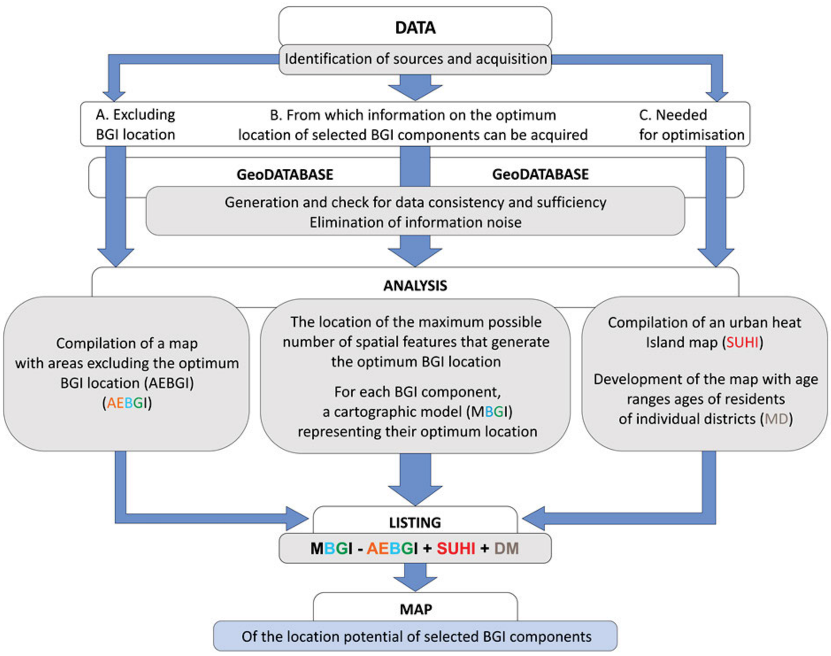

Fig. 1. The geoinformation analysis undertaken in the study; BGI = blue-green infrastructure, AEBGI = areas excluding blue-green infrastructure, MBGI = model of blue-green infrastructure optimum location, SUHI = surface urban heat island, DM = demographic model; source: own elaboration

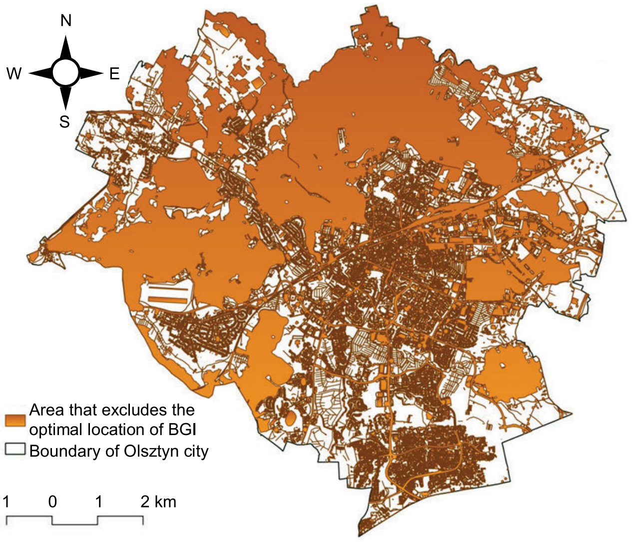

Fig. 2. Visualisation of the first group of data used for the analysis, which forms the layer of features excluding the optimum BGI (blue-green infrastructure) location for the Olsztyn city; source: own study

The third group (group C) comprises data that are used to develop the SUHI model and the map showing demography in the area under analysis (DM model).

GEOINFORMATION DATA AND ANALYSIS TO IDENTIFINE THE OPTIMUM BGI LOCATION (MBGI)

Analyses performed using a geoinformation application allow to analyse with larger precision phenomena and processes occurring in space. However, it should be noted in each case the completeness of a solution mainly depends on the quality of data used. It was therefore decided to use the spatial datasets maintained within the National Land Surveying and Cartographic Resource. The data used to identify significant spatial features for the location of particular BGI components are listed in the Table 2.

The analyses focused on two datasets: BDOT10k and DTM. The first constitutes a vector database containing information about spatial location and basic characteristics of topographic objects, enabling the creation of cartographic materials at a scale of 1:10,000. The data is acquired from measurements and integrated based on existing reference databases belonging to the National Land Surveying and Cartographic Resource (Pol.: Państwowy Zasób Geodezyjny i Kartograficzny). The assumption regarding updates stipulates that the data should be updated within a maximum period of two years, and the maximum positional error for objects in this dataset is 1 m. As proposed by the authors, the data can be complemented with vector data from the Open Street Map, taking into account that in selected areas within the city the data may be more up to date. However, it should be noted that currently only the BDOT10k dataset provides a sufficiently broad scope as well as data quality for the entire country.

Table 2. The data used in analyses concerning blue-green infrastructure (BGI)

Data set	Organisation	Date acquired
Hydrological corrections	SCALGO	29.03.2023
DTM	GUGiK	20.03.2023
BDOT10k (surface water)	GUGiK	27.10.2020
BDOT10k	GUGiK	29.03.2023
OSM	OSM	29.03.2023

Explanations: DTM = Digital Terrain Model, BDOT10k = Topographic Reference Database, OSM = Open Street Map.
Source: own elaboration.

On the other hand, the second dataset (DTM) is a discrete (point-based) representation of terrain elevation developed through aerial laser scanning (ALS). The analyses uses a Grid model with a 1 × 1 m grid to present terrain elevation in the PL-KRON86-NH coordinate system. This format is more widely used in reference to geoinformation systems compared to the TIN (triangulated irregular network) model. Due to its organised structure, data archiving ease, and greater suitability for spatial analyses, the authors adopted this method of surface representation. It should also be noted that in the Grid model, heights at nodal points typically have interpolated values. For the applied data, the average height error is 0.1 m.

In terms of their different configuration as well as the respective tools used for analyses, the above data enabled to establish procedures for determining optimum locations for BGI components, in particular, taking into account the features provided in Table 1. In order to systematise actions taken, the authors decided to describe each component in a separate subsection.

Water retention pond

The first BGI component which was analysed by the authors in terms of geoinformation was the water retention pond. In the spatial analysis of the BGI element, the locational features considered included the presence of depressional areas in the city prone to flooding with minimum rainfall of 10 mm, positioning of drainage facilities, absence of any connection to existing water bodies, minimum and maximum catchment areas, and the planned water retention pond. Simultaneously, based on the favourable features, optimal locations were identified within park areas and urban squares. The aforementioned factors were determined as spatial features conducive to the presence of the selected BGI element.

In view of the assumptions made (Tab. 1), the authors considered, in the first instance, natural depressions of the land in order to determine the optimum locations. To this end, topographic data with a spatial resolution of 1×1 m (DTM), as well as data on buildings extracted from the BDOT10k dataset were used. When selecting the optimum locations, it was assumed that the analysis would cover depressions in the land with an area ranging from 3 to 7% of the drainage area with an area ranging from 3 ha to a maximum 10 ha, representing the area of the drainage basin. As a result of converting the assumed quantities, facilities with a minimum area of 900 m^2, and a maximum area of 7000 m^2, were selected for further analyses. At the same time, as part of the adopted assumptions concerning the BGI component concerned, the water retention pond could not have contact with the existing natural water bodies. Therefore, a 100 m buffer zone was established around the existing water bodies to eliminate land depressions connected to or located close to the water bodies under analysis. The analysed spatial range concerned areas for which information on land surface temperature (LST) was acquired. Subsequently, meteorological data of 1981–2019 from the IMGW-PIB meteorological station in Olsztyn (IMGW, 2023) were used as part of the analysis concerning the retention nature of the facilities. Since the analysis of the land surface temperature (LST) was carried out for the summer period, the maximum daily rainfall for the city of Olsztyn was analysed, in particular, high-intensity rainfall of 10 mm or more. According to the meteorological data acquired, the number of days with high-intensity rainfall ranged from 15 to 16 per year, showing an increasing trend of 1.5 days per decade.

Flooded areas were then designated in the city area for rainfall of 10 mm and more using the SCALGO application. Based on the BDOT10k dataset, the next step involved the development of a set of features conducive to the establishment of ponds in a particular area. The update of the designated use topographical facilities (parks, public spaces) enabled us to identify areas suitable for the location of the above-mentioned project. In the next step, based on the BDOT10k dataset supplemented with OSM data, the study focused on the location of water retention ponds in relation to the existing drainage facilities, i.e. drainage ditches, gutters, and minor watercourses which were not indicated as flowing waters. Based on the BDOT10k dataset, facility classes of SWRM (water network-drainage ditches), SWKN (water network-canals) and SWRS (water network-rivers and streams) were used, while for the OSM, the facility class waterway was used. The actual circulation of water also depends on the catchment areas formed by rainwater drainage systems. However, the complexity of this issue is a separate area of research, which the authors will try to deepen in further stages of the study. Due to the nature of this data in terms of the high dynamics of changes in the system and the problem with availability, the data were not included in the analysis. The identification of the location of these facilities enabled to implement the retention function as well as the additional rainwater purification function. The placement of the water retention pond in proximity to the analysed water facilities, which serve as habitats for a diverse range of organisms, enhances environmental biodiversity and contributes to the overall improvement of the urban landscape. Finally, spatial analyses concerning features supporting the use of the water retention pond were conducted in two variants. The first variant assumed the use of spatial features, including favourable land use, the determination of locations of land depressions of the dimensions indicated, and the lack of possibility to locate them in the buffer zone established at a distance of 100 m from the existing water bodies. The analytical process comprised the following steps performed in the ArcGIS application (Fig. 3).

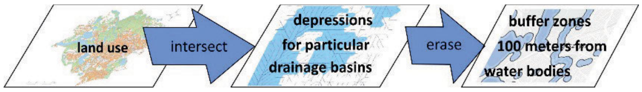

Fig. 3. The determination of locations of specific land depressions; source: own elaboration

Thus, in accordance with the assumptions provided in Table 1, the basic set of features, when appropriately configured, enables to optimise the location of the water retention pond. The analysis identified 349 potential locations for the water retention pond in the Olsztyn city area. However, with these considerations in mind and taking into account the possibility of expanding the set of features analysed, the authors additionally proposed that drainage facilities and flooded areas were considered in the analysis for significant daily rainfall of 10 mm and more. The analysis was extended to cover additional functions of the water retention pond, which in addition to reducing the temperature in a particular area might increase the retention as well as water purification in a particular area. The analytical process is shown in Figure 4.

The analysis, which involved the set of excluded areas AEBGI (Fig. 2), identified 31 areas for which the set of features favours the location of water retention ponds. Ultimately, due to the broader approach taken in the analysis, optimum use of space through the implementation of both the function of temperature reduction in the city, as well as the retention and purifying functions, it was decided to choose the second scenario for further research to cover maps with potential locations of BGI (Fig. 5).

Bioretention basin

As regards the second component that was analysed in terms of the BGI location potential in the city area, the authors focused on its retention function. This time the spatial analysis focused on the bioretention basin and covered the location features for minimum and maximum catchment areas. Simultaneously, based on the favourable features analysed, optimal locations were identified within heavily urbanised areas and firmly sealed surfaces. The factors considered included spatial features conducive to the presence of the selected BGI element.

While determining the optimum areas for the location of bioretention basins using the SCALGO software, sub-drainage basins were established while assuming a minimum daily rainfall of 10 mm. Then, in accordance with Table 1, it was assumed that drainage basins with a maximum area of 2 ha would be analysed. Since this component of blue-green infrastructure could be designed on a small scale, no minimum area was assumed for them. The analysis demonstrated that 26,400 such drainage basins could be distinguished in the city area. In the next step, facilities presenting information on land coverage, e.g. squares, car parks, and urbanised areas (residential communities) were extracted from the BDOT10k dataset as the areas preferred for the location of bioretention basins. Therefore, in the next step of the analysis, drainage basins with a maximum area of 2 ha, located in the areas indicated for the location of the BGI component were selected. The procedure is shown in Figure 6.

The analyses provided the authors with three spatial datasets accounting for 679, 519, and 8,326 drainage basins in the areas sequentially representing squares, car parks and residential communities. Based on the layer of excluded areas AEBGI (Fig. 1), the selection process prioritised sub-drainage basins

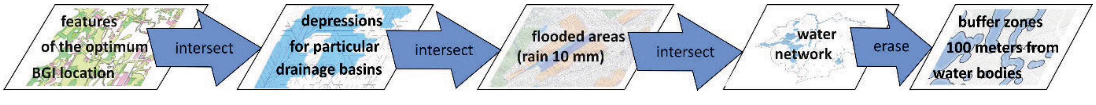

Fig. 4. Geodata analytical process for optimal location of retention pond; source: own elaboration

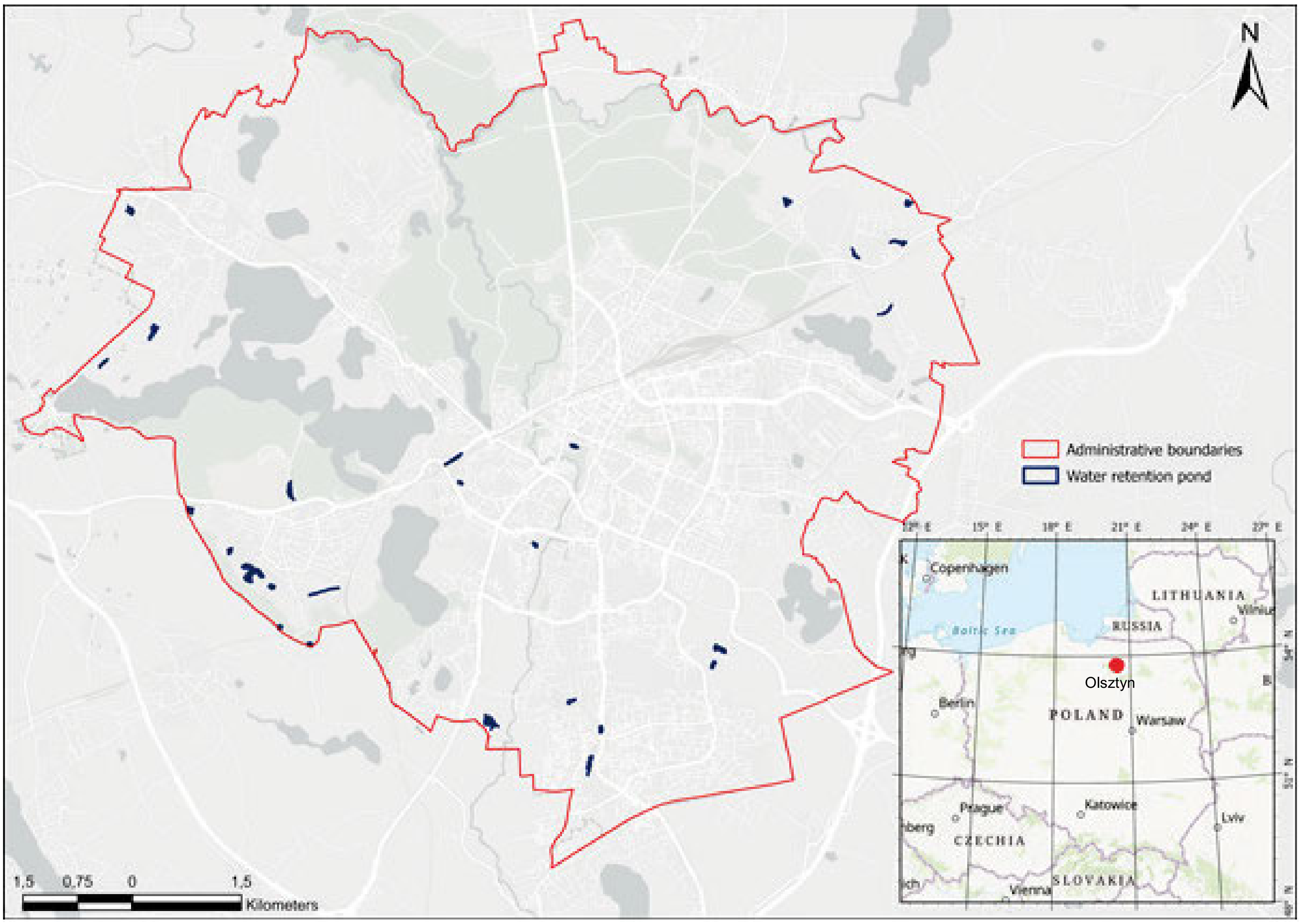

Fig. 5. A cartographic model (MBGI-model of blue-green infrastructure optimum location) representing optimum location of water retention ponds in the Olsztyn city; source: own study

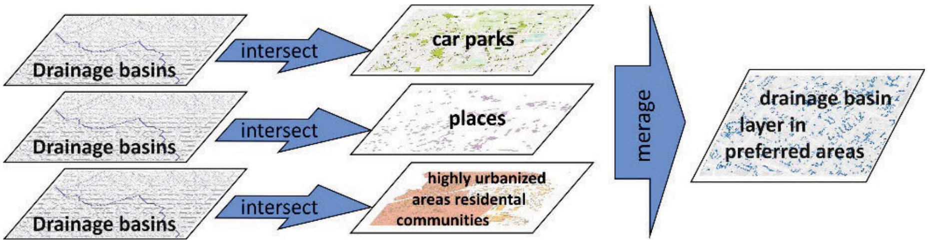

Fig. 6. Geodata analytical process for optimal location of bioretention basin; source: own elaboration

that had the potential for the implementation of the BGI component, taking into account the broader spatial extent of the spatial coverage data and the limitations involved. Finally, the authors identified 506 drainage basins within the city area, which served as the foundation for developing an MBGI cartographic model capable of identifying optimal locations for the bioretention basin (Fig. 7).

SURFACE URBAN HEAT ISLAND (SUHI) MODEL AND DEMOGRAPHIC MODEL (DM)

Surface urban heat island (SUHI) model for the city of Olsztyn

In order to calculate the urban heat island, the land surface temperature (LST) had to be calculated based on the Landsat 8 mission data. Since the spatial extent of one scene is 185 × 180 km, it was possible to capture the Olsztyn city area in a single image. According to the recommendation of the United States Geological Survey (USGS), data from the Thermal Infrared Sensor (TIRS) with a spatial resolution of 30 m for channel 10 were used (U.S. Geological Survey, 2019). The procedure that enables the performance of a precise measurement assumed the consideration of an atmospheric correction and different emissivity depending on the nature of the surface. To this end, the study used the Single-Channel Algorithm method (Jimenez-Munoz *et al.*, 2009) which by using atmospheric functions, atmospheric correction, and the Normalized Different Vegetation Index Thresholds method, i.e. active emissivity thresholds using the *NDVI* (normalized different vegetation index), allows to be taken into account in the measurement (Sobrino *et al.*, 2008). Given the method performance confirmed in numerous studies, in particular in relation to the Landsat-8

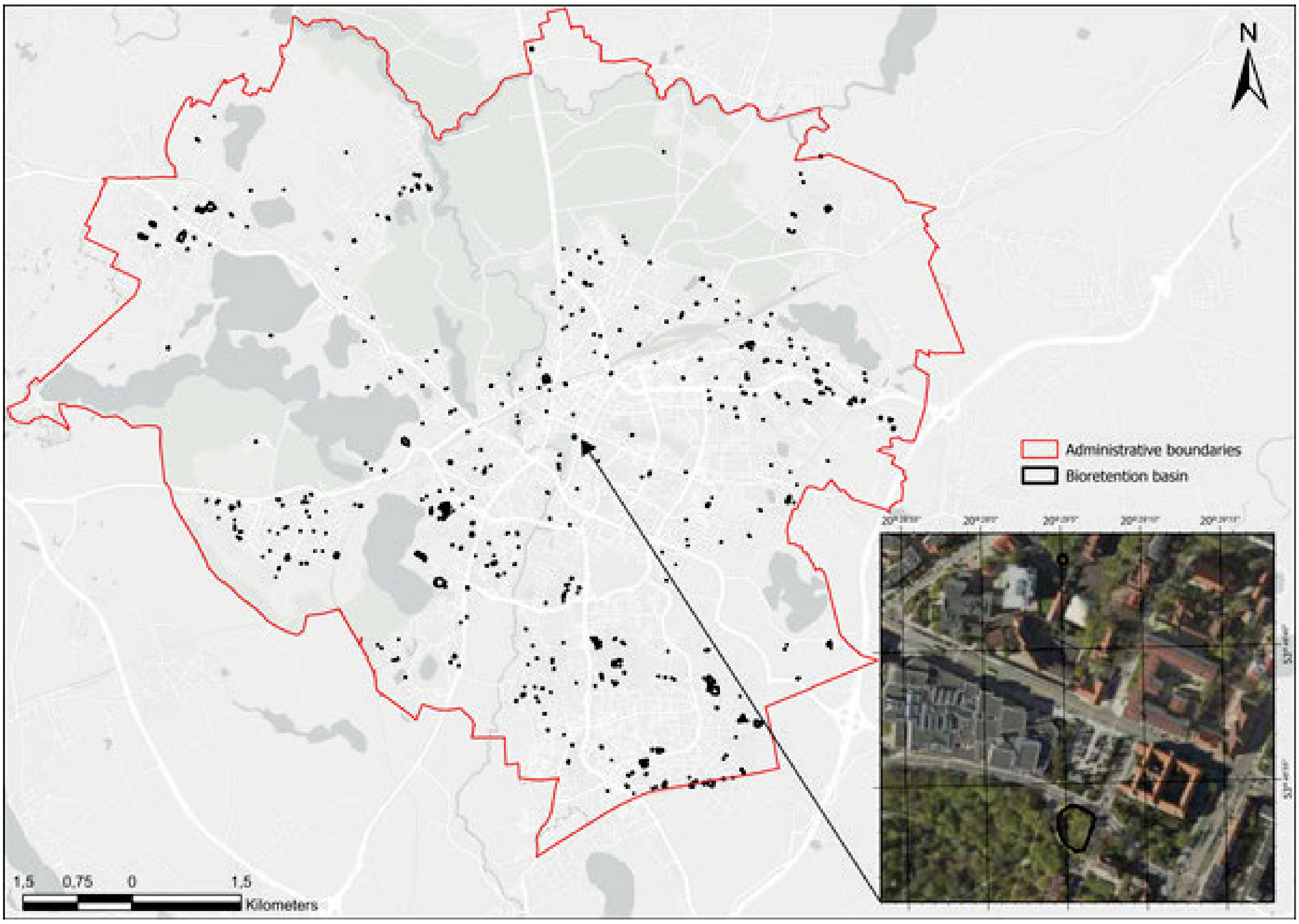

Fig. 7. A cartographic model (MBGI) representing the bioretention basins optimum location for the Olsztyn city; source: own elaboration

OLI/TIRS mission data, it was decided to apply the methodology described in the study (Jimenez-Munoz *et al.*, 2009; Gábor and Jombach, 2010). It should also be noted that as far as the currently developed methods are concerned, the most accurate results are presented by the method developed by Sobrino *et al.* (Sekertekin and Bonafoni, 2020). The methodology is presented in Figure 8.

Due to the duration of the satellite acquisition over the area under analysis, the maximum temperature set for the hour 10:00 was selected for comparison. Based on historical meteorological data, it was determined that the highest temperature of 30.9°C (Valor, 2023) was noted on 28 June 2022 (Barsi, Barker and Schott, 2003). In view of this fact, it was decided to use the data from the day concerned for further analysis. The results are shown in the cartographic model in Figure 9.

Demographic model (DM)

In order to analyse the age structure in the study area, demographic data provided by the Vital Records Office and the Public Service Department of the Olsztyn Municipal Office in tabular form were used. The acquired and aggregated data were then juxtaposed with the data on residential community boundaries. The analysis allowed the population to be divided by the following age groups: 0–10, 11–65, over 65, to particular residential communities. In turn, the percentage of people aged over 65, who are particularly vulnerable to the adverse effects of high summer temperatures, in the total population in residential communities (DM) is shown in the map – Figure 10.

MAP OF THE LOCATION POTENTIAL OF SELECTED BLUE-GREEN INFRASTRUCTURE COMPONENTS

In the subsequent stage of the research, the MBGI cartographic models depicting the optimal locations of individual blue-green infrastructure components were juxtaposed with the study showing surface urban heat islands (SUHI) and the demographic model (DM) (Fig. 11).

The aim of this step was to provide clear solutions in specific locations within the studied city area by aggregating individual BGI components and relating them to temperature distribution and resident age structure. As a result, the developed MBGI cartographic models served as a tool for visualising, analysing, and selecting optimal BGI locations of the largest positive impact on temperature reduction. Thus, BGI could improve the quality of urban life and enhance the resilience of the elderly population, particularly vulnerable to the effects of extreme climate changes. The mitigation of adverse effects of high temperatures is directly related to the reduction of such risks as hyperthermia, dehydration, exacerbation of chronic illnesses, social isolation, and sleep disturbances. Therefore, especially concerning the aging population, it is crucial to implement appropriate measures to counteract heat-related effects, disseminate information about how to protect against extreme temperatures, and establish systems that support vulnerable individuals during heatwave events.

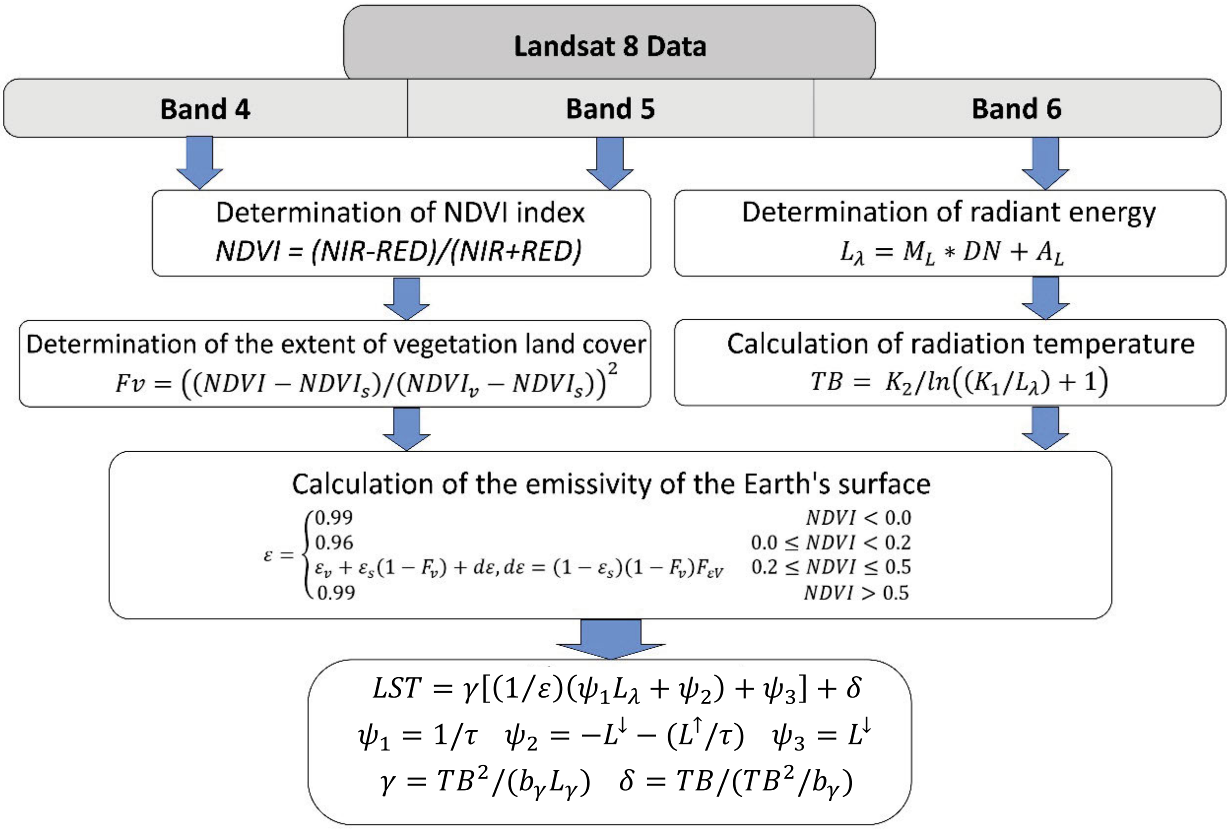

Fig. 8. Land surface temperature (*LST*) data acquisition method: *NDVI* = normalized different vegetation index, *NIR* = represents the spectral channel in the red wavelength range (channel 4 for Landsat 8), *RED* = represents the spectral channel in the near-infrared wavelength range (channel 5 for Landsat 8), L_λ = spectral radiance at the upper boundary of the atmosphere (W·m^{-2}·sr^{-1}·μm^{-1}), M_L = conversion factor for channel 10 (M_L = 0.0003342), *DN* = 32-bit digital value of the thermal channel, A_L = conversion factor for channel 10 (A_L = 0.1), F_v = extent of vegetation land cover, $NDVI_s$ = standardised vegetation index for bare land, $NDVI_v$ = standardised vegetation index for areas covered with vegetation, *TB* = radiation temperature, K_1 = a constant for the particular wavelength related to the first radiation constant c_1 (K_1 = 774.8853), K_2 = a constant for the particular wavelength related to the second radiation constant c_2 (K_2 = 1321.0789), ε = land surface emissivity index, ε_v = emissivity of full vegetation index, ε_s = emissivity of bare soil index, $d\varepsilon$ = geometrical distribution of the natural surfaces and internal reflections index ($d\varepsilon$ = 0.55), $F_{\varepsilon v}$ = geometrical shape factor assumed as the mean value of 0.55, *LST* = land surface temperature, γ and δ = parameters obtained from the linear approximation of the Planck's law, ψ_1, ψ_2, ψ_3 = atmospheric functions, τ = band average atmospheric transmission (τ = 0.70), $L^\uparrow$ = effective bandpass upwelling radiance ($L^\uparrow$ = 2.45 W·m^{-2}·sr^{-1}·um^{-1}), $L_\downarrow$ = effective bandpass downwelling radiance ($L_\downarrow$ = 4.06 W·m^{-2}·sr^{-1}·um^{-1}), b_γ = conversion parameter for Landsat 8 TIRS band 10 (b_γ = 1324); source: own elaboration acc. to Sobrino *et al.* (2008), Jimenez-Munoz *et al.* (2009), Sekertekin and Bonafoni (2020)

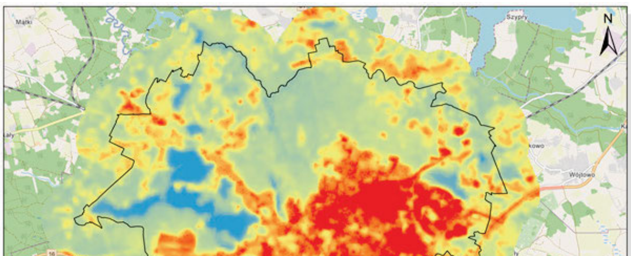

Fig. 9. Surface urban heat island (SUHI) for the Olsztyn city area, developed based on Landsat 8 data; source: own study

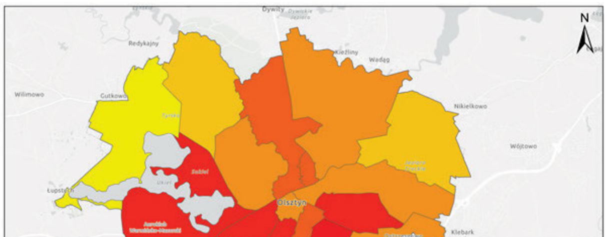

Fig. 10. Demographic model representing the percentage of the elderly in the total population of inhabitants of particular residential communities in Olsztyn city; source: own study

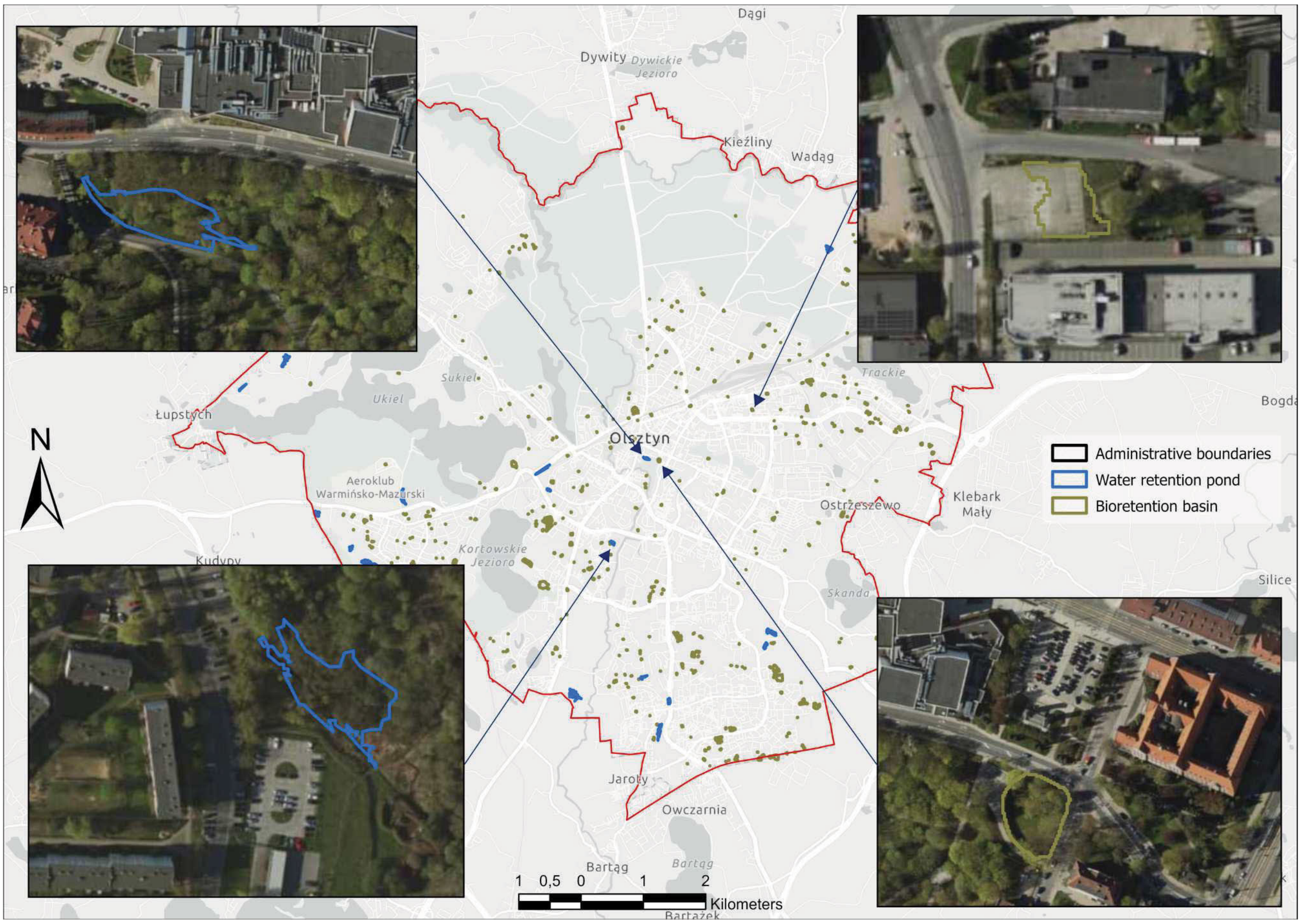

Fig. 11. Location potential of selected blue-green infrastructure components for the Olsztyn city; source: own elaboration

RESULTS AND DISCUSSION

As part of the analysis, the authors noted that data quality was the crucial component of the study concerned. Based on BDOT10k data, it was concluded that problems related to data completeness and timeliness occurred in the dataset under analysis. Despite the fact that the topographic database is updated at least every two years, changes in spatial development are dynamic and not all components are represented in the database.

Considering that BDOT10k data is available in a vector format, there is a possibility of integrating it with other datasets, thereby facilitating quality control of individual datasets and maintaining up to date information in the final dataset. In light of the above, the authors decided to integrate OSM data with the BDOT10k dataset as part of the research process.

After considering the strengths and weaknesses of each dataset, the decision was made to integrate them. On one hand, BDOT10k, based on the fundamental map and serving as a baseline resource for investment, allowed to identify crucial technical infrastructure elements that might escape attention when editing maps on the OSM platform. On the other hand, the speed of updates favoured the identification of elements that might have been overlooked during updates or constructed between individual update cycles. The incorporation of data from diverse sources facilitated mutual comparison and validation, which, according to the authors, enhanced the accuracy of the analysis.

Another component observed by the authors, which should also be addressed in the context of the results obtained, is the method for determining the land surface temperature (LST) to determine the surface urban heat island (SUHI). Although this method has been repeatedly applied in such analyses, it has its limitations. The main advantage is the possibility of acquiring simultaneous thermal imaging for the entire city. In contrast, the only problem is the fragmentary acquisition of data on thermal radiation from vertical surfaces as well as the correct understanding of emissive properties of different parts of the substrate. As part of the study, the authors carefully identified suitable land uses in order to determine their emissivity coefficients. Moreover, atmospheric corrections, for which certain simplifications and generalisations were assumed, were also applied. The last component, which, unfortunately, could not be eliminated, was the time of data acquisition. Literature reviews show that the SUHI phenomenon intensifies during night hours. In contrast, satellite data are recorded in Poland during daytime which, for the city of Olsztyn and for the selected data sets, fell between 09:30 AM and 10:00 AM. Nevertheless, the authors concluded that the optimum locations for BGI could be indicated based on the data. Then, using air temperature measurements at particular locations, data validity could be confirmed.

As part of the research, demographic data that required elaboration and aggregation were used. Unfortunately, it was not possible to assign these data to all specific locations but only to residential communities. Although the data showed the actual age structure in the city, it did not enable to determine a precise distribution of inhabitants and assigning them to specific buildings.

Ultimately, in a practical dimension, the developed cartographic models can serve as pivotal tools for decision-makers and urban planners and contribute to enhancing the quality of residents' lives and bolstering resilience to climate change. On the other hand, the research revealed limitations concerning the completeness and timeliness of data, which subsequently affected the accuracy of the analysis results. Furthermore, within the scope of the study, aspects such as soil and ground conditions, infiltration capacity of the subsoil, depth of the groundwater table, and the city‘s ventilation model were not taken into account. However, the authors believe that the models they developed could serve as a starting point for further analyses incorporating additional spatial features relevant to the deployment of blue-green infrastructure.

CONCLUSIONS

This study demonstrates that the use of geoinformation systems, both at the stage of data acquisition and integration as well as subsequent spatial analyses, is an extremely effective tool when compiling maps of optimum locations for selected blue-green infrastructure (BGI) components. The method used allows to choose areas which, due to their spatial features, are optimum locations for the deployment of blue-green infrastructure components. Due to the enhanced availability of spatial data and open Geographical Information System (GIS) tools, the method supports considerable degree of automation.

In the analysis presented in this paper, the models developed, such as the urban heat island model and the demographic model, serve the role of filters and provide additional geospatial information. It is particularly justified and logical to design and distribute BGI in areas where heat islands are found, as well as in residential areas and locations of active elderly communities. When justifying the necessity of the research presented in the paper, the following benefits should be pointed out:

- increase in the planning efficiency based on an optimum BGI deployment map. Thus, the planning of urban infrastructure can be more effective. Consequently, this enables better use of space, minimises conflicts with existing structure, and ensures optimum BGI distribution, which translates into better environmental, social, and economic outcomes;
- improvement of the inhabitants' quality of life, where BGI components, such as parks, rain gardens, and water retention facilities have a direct positive impact on life quality. The appropriate distribution of these components in strategic locations can improve air quality, reduce the effects of surface urban heat islands, increase access to green spaces, and improve the overall aesthetic value and attractiveness of the city;
- adaptation to climate change as a major challenge for cities with BGI playing a key role in the adaptation process. The study into optimum locations of BGI components takes into account climatic factors, such as rainfall intensity, temperatures, and flooding vulnerability. This enables the city to adapt effectively to climate change;
- implementation of the sustainable development policy through the identification and selection of locations for BGI. This promotes a sustainable urban development while maintaining harmony between the natural environment and human activity, particularly in terms of urban suburbanisation processes.

In the light of this analysis, other important factors include data on soil and ground conditions, infiltration capacity of the subsoil, depth of the ground water table and the city's ventilation model. Due to the nature of these data, their complexity, form, and their limited availability, the data were not included in the analysis. The current model, including a map of BGI's development potential, delineates areas that can be verified by these data, i.e. the model provides the base material for further analysis.

The study is the preliminary step to develop a matrix of optional locations and, consequently, maps of alternative locations for the deployment of blue-green infrastructure. Further analyses will enable more accurate assessment and selection of optimum locations taking into account a variety of social, spatial, and environmental factors. Further research and the development of this method will be essential for the effective design and implementation of BGI aimed at improving the quality of life in urban communities.

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